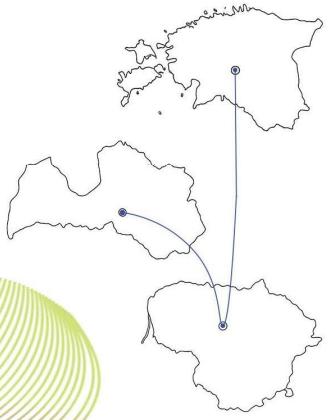
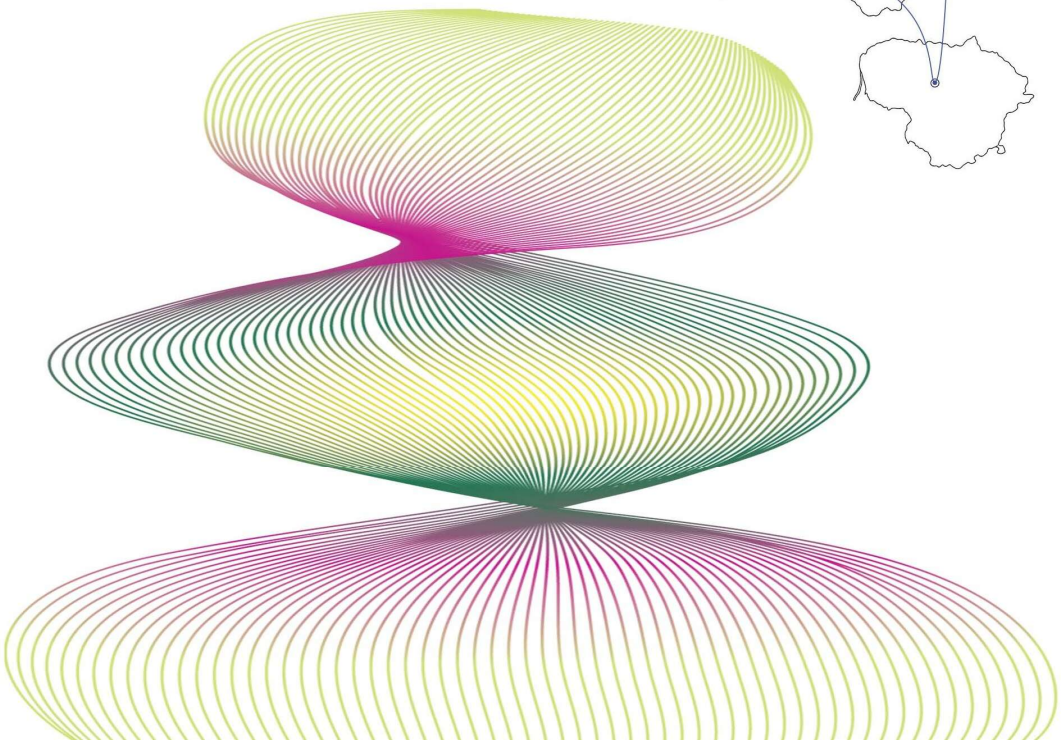
SCIENCE AND TECHNOLOGY EDUCATION: EXPECTATIONS AND EXPERIENCES

Proceedings of the 6th International Baltic Symposium on Science and Technology Education (BalticSTE2025), Šiauliai, 16–19 June, 2025

Vincentas Lamanauskas (Ed.)





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Contents

Introduction to the Proceedings

NATURAL SCIENCE AND TECHNOLOGY EDUCATION: BalticSTE2025
Vincentas Lamanauskas 7

Articles

EDUCATION TRANSFORMATION FOR NET GENERATION
Boris Aberšek, Metka Kordigel Aberšek 11

A STEM APPROACH TO STANDARD SCIENCE CURRICULUM TOPICS: CHEMICAL REACTIONS AS A TYPICAL EXAMPLE
Martin Bílek, Karel Kolář, Monika Pelikánová 18

DEVELOPMENT OF THE CONTENT OF THE "BIOLOGY I" SET OF METHODOLOGICAL MATERIALS FOR A COMPETENCE-BASED APPROACH TO SECONDARY SCHOOL BIOLOGY
Rita Birzina, Daiga Kalnina, Sandra Kalnina 30

THE CONCEPT OF FORCE: AN EDUCATIONAL ITINERARY WITH A HISTORICAL SUPPORT
Paolo Bussotti 47

INTEGRATING MULTIMODAL TEACHING STRATEGIES INTO STEM EDUCATION: REFLECTIONS FROM PRE-SERVICE AND IN-SERVICE TEACHER WORKSHOP EXPERIENCES
Narendra D. Deshmukh, Sandhya A. Thakur 71

THE ROLE OF LEADERSHIP IN CURRICULUM TRANSFORMATION: IMPLICATIONS FOR SCIENCE, TECHNOLOGY, ENGINEERING, ARTS AND MATHEMATICS IN HIGHER EDUCATION
Angela James, Cecile Gerwel Proches, Macdonald Kanyangale, Valentina Dagienė, Eglė Jasutė, Roger Waldeck 86

REIMAGINING PRESCHOOL PEDAGOGY: AI-ENHANCED TEACHING THROUGH MULTILITERACIES-INFORMED CURRICULUM INNOVATION
Kallia Katsampoxaki-Hodgetts, Konstantinos Kotsidis, Stamatios Papadakis, Panagiotis Anastasiades 104

METACOGNITIVE STRATEGIES FOR READING SCIENTIFIC AND SUSTAINABILITY-RELATED CONTENT IN DIGITAL AND PRINT MEDIA
Maja Kerneža 120

PRE-SERVICE PRESCHOOL AND PRIMARY SCHOOL TEACHERS' ATTITUDES ON ARTIFICIAL INTELLIGENCE: READINESS TO USE AND POTENTIAL CHALLENGES
Vincentas Lamanauskas 133

BRIDGING DISCIPLINES: THE ROLE OF MATHEMATICAL REASONING IN INTERDISCIPLINARY INQUIRY
Arto Mutanen, Antti Rissanen, Kalle Saastamoinen 146

SCIENCE EDUCATION FOR STUDENTS WITH SPECIFIC LEARNING AND ATTENTION DISORDERS: AN EVALUATION OF READING STRATEGIES USING EYE-TRACKING TECHNOLOGY
Aušrinė Raudoniūtė 158

GENERATING CURRICULA: A HUMAN-CENTRED PERSPECTIVE IN THE ERA OF ARTIFICIAL INTELLIGENCE
Tiia Rüütmann, Urve Läänemets 180

LANDOLT TABLES IN PRIMO LEVI'S "BEST IS WATER" FOR VALUE-BASED CHEMICAL EDUCATION
Uladzimir K. Slabin 197

Information

KEYNOTE SPEAKERS 211

SYMPOSIUM POSTER 214

BalticSTE2027 215

NATURAL SCIENCE EDUCATION / GAMTAMOKSLINIS UGDYMAS 216

JBSE 217

NATURAL SCIENCE AND TECHNOLOGY EDUCATION: BalticSTE2025

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Natural Science and Technology Education (NSTE) is very important in the modern world, and there is probably no doubt about that. Understandably, it was important before, however, each era creates different challenges. It is obvious that science and technology are rapidly changing everything, especially the world of work. For example, knowledge about STEM (Science, Technology, Engineering, Mathematics) fields should help the younger generation acquire promising professions related to artificial intelligence, robotics, bioengineering, and other innovative disciplines. In addition, natural science and technology education forms/develops analytical thinking, experimentation, and logical decision making. These skills are needed not only in science but also in everyday life and the business world. Today's STE education, like any other field of education, requires scientific research, the result analysis of which would help to understand the gaps in the teaching process organisation, and help to find new didactic instruments (Schneider & Oberländer, 2008). Research shows that technology integration is changing STE education. It is emphasised that technologies increase student engagement, improve learning outcomes, and develop the essential scientific research skills. The use of technologies allows for the application of interactive and collaborative teaching methods, provides more opportunities for practical learning, and personalised education (Tindan & Rahaman, 2024). On the other hand, technologies help to develop creativity, problem-solving skills, and sustainable development competencies, especially relevant for the 21st-century labour market (Puchongprawet & Chantraukrit, 2022). It is crucial to educate students on the basis of science, technology, engineering, and mathematics (STEM) education to develop 21st-century learning skills (Xu & Zhou, 2022). Understandably, education and workforce competencies are considered vital for the digitalisation of various economic sectors at both macro and micro levels (Uzule et al., 2024). Finally, recent challenges relate to natural science/digital literacy education (how to begin to develop science literacy skills) (Kordigel Aberšek, 2008), and AI application in the natural science and technology education process (Aberšek, 2023).

Although natural science and technology education has been reformed in Lithuania, however, the results are not encouraging. The current task for the entire educational community remains how to make science and technology subjects attractive to students, so that they seek to connect their future careers with science and technology. It is understandable that school alone is unable to solve this complex task. The situation is determined by the general political-economic and, of course, social situation of the country. However, properly organised natural science and technology education in a general education school can significantly change the situation. The school's duty is not to develop specialised science and technology subject teaching at school, but specifically general science and technology education, so that each student acquires science and

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technology education that is adequate for the time (Lamanauskas, 2008; 2015a). It is also clear that the implementation of technology in schools requires investment in equipment and teacher training, but it brings clear benefits – improves student understanding and facilitates the conveyance of complex scientific concepts. Research results show that both teachers and students acknowledge the benefits of technologies, especially the use of digital tools explaining complex topics and increasing student motivation (Slotta, 2014).

Thus, BalticSTE (Baltic Symposium on Science and Technology Education) is an international, biennial scientific event, the aim of which is to promote a dialogue, research development, and innovation in the field of natural science and technology education. The first symposium took place in 2015 in Šiauliai, Lithuania, and since then has become a significant platform that brings together scientists, researchers, and the educational practice community from different countries for constructive discourse and cooperation (Lamanauskas, 2015b). Later, other symposia were successfully held, namely the second in 2017 (Lamanauskas, 2017) and two years later, the third (Lamanauskas, 2019). The fourth BalticSTE2021 symposium was held remotely due to the ongoing COVID-19 pandemic at that time. However, despite various challenges, the fourth symposium was successful (Lamanauskas, 2021). Of course, after the Covid-19 pandemic ended, the fifth BalticSTE2023 symposium took place as usual, in Šiauliai (Lamanauskas, 2023). The symposium was held in cooperation with Povilas Višinskis Šiauliai County Public Library, and Šiauliai Technology Training Centre. These were the two main partners of the symposium. The articles of all scientific symposia were published in collections that can be found in academic databases (ERIC, Google Scholar, ResearchGate, CEEOL, etc.). It is worth mentioning that a publication was prepared, which retrospectively reviews all five symposia that took place. The book entitled *BalticSTE Symposia Retrospective: Five Milestones in Science and Technology Education (2015–2023)* offers an in-depth look at the evolution of science and technology education through the lens of five international BalticSTE symposia held in Lithuania (Lamanauskas, 2025). Drawing from over two decades of national and international educational initiatives, the book captures the dynamic shifts in pedagogical practices, technological integration, and competency development in natural science and STEM fields. Topics covered include innovative teaching methodologies, the impact of emerging technologies such as AI and IoT, interdisciplinary approaches like STEAM, and education for sustainability and social responsibility. Serving as both a historical record and a resource for future educational strategies, this retrospective highlights the significance of international collaboration and research-driven practice in shaping contemporary education.

This, the sixth BalticSTE2025 symposium, once again demonstrates a consistent and growing interest in natural science and technology education, which is gaining even greater importance in the modern knowledge society. Science and digital literacy, technological competence, and interdisciplinary thinking are becoming essential skills that allow an individual to effectively navigate and act responsibly in a rapidly changing world. It is obvious that scientific research in the field of science and technology education is of particular importance. First of all, because the current and future world is facing complex challenges, such as climate change, sustainability crisis, healthcare, digitalisation, and the development of artificial intelligence. For people to be able to critically assess and solve such problems, a high level of scientific and technological

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literacy is necessary. Research in this area helps to understand how education can form such competencies. The BalticSTE symposium provides a platform for international dialogue between scientists. By presenting research here, it is possible not only to share results but also to compare experiences between countries, to discover common trends or distinctive regional features. In addition, the symposium brings together researchers from various fields – natural sciences, technology, engineering, mathematics, and education, promoting an integrated approach to educational problems and solutions.

This collection of scientific articles covers a wide range of topics: from curriculum renewal and competency-based education to advanced methodologies, such as metacognitive strategies, application of artificial intelligence, or multimodal teaching methods. Attention is also paid to the aspects of inclusion, integration of sustainability themes, and the role of leadership in the context of educational change.

We hope that this collection will serve as a valuable resource not only for educational researchers but also for educational practitioners and policymakers seeking sound, evidence-based decisions and sustainable educational development. The BalticSTE symposium continues to be a significant space for constructive collaboration, reflection, and promotion of progress in the field of natural science and technology education.

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EDUCATION TRANSFORMATION FOR NET GENERATION

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Abstract

When life (society) changes rapidly and drastically, school (education) must change accordingly. However, not all changes are good and beneficial for society, so schools must also think critically and work with a time lag that allows for critical reflection and the search for more rational and optimal solutions.
Teachers remain essential in the educational process, but their role changes drastically. This shift should not stem from random decisions by inventive individuals but rather from carefully considered reflections on new pedagogical paradigms. Today, this is called digital pedagogy, which inevitably transitions into generative pedagogy. Moreover, the shift from one to the other is discreet yet represents a quantum leap in an extremely short time. However, the teacher/human is no longer primarily a holder and transmitter of knowledge. Instead, their role increasingly shifts toward education in the affective domain, where they become facilitators of relationship-building and human values.
Keywords: *digital pedagogy, generative pedagogy, net generation, education transformation*

Introduction

Sartre warns that existential questions cannot be answered once and for all. Philosophical questions, by definition, are questions that generations must constantly ask themselves, as this fosters a vivid sense of being alive in us (Sartre, 1984).

The school is more than ever at a crossroads and needs drastic rethinking. A system of constant change is no longer sufficient, but we need a comprehensive renewal, especially in the pedagogical and didactic fields. We must proceed from the fundamental theses of the school as an educational institution, which must develop students as a comprehensive personality. Therefore, it must consider all three fundamental starting points of Bloom's original taxonomy (Bloom, 1956) and all taxonomies developing from it, e.g., the revised Bloom taxonomy (Krathwohl & Anderson, 2001). However, the two fundamental theses still have to remain

1. that the school, is a school for life, and
2. that life (society) is changing faster and more drastically.

From these two premises, if life (society) changes rapidly and drastically, school (education) must change accordingly. Of course, we must be aware that not all changes are good and beneficial for society. So, the school must also think critically and work with a time lag that allows for critical reflection and the search for perhaps more rational and optimal solutions.

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By following these assumptions, we can develop a learner-centred strategy for education from the turn of the 20th century to the 21st century. Based on the generations that meet in today's educational process in formal or various non-formal forms of education, we focus on the transition from Millennials (1981 – 1995) and further Generation Z (Gen Z – 1995 – 2012), colloquially known as Zoomers, which represent the demographic cohort succeeding Millennials and preceding to the Generation Alpha, born between 2010 and 2024. The reason named them Generation Alpha is because they are not a return to the old, but the start of something new. Even more than their parents' generation (the Millennials), there is a greater sense of Generation Alpha being shaped in the new millennium. The fusion of these generations is briefly called the Net (Web) generation.

In short, the school, which should be synonymous with society and education at the turn of the 20th century to the 21st century, is undergoing drastic changes, at least for two key reasons, namely:

1. because technological possibilities allow us to take completely different approaches, strategies, and opportunities for learning and teaching, and
2. because the learners are entirely different from those who were educated during the development of the fundamental pedagogical doctrine, e.g., in the case of digital pedagogy from the end of the twentieth and the beginning of the 21st century.

From the second premise that learners are different and acquire knowledge and skills in different ways, it is necessary to derive additional theses. Analyzing the Web generation reveals several key shifts (Aberšek, 2024). The world is no longer singular; instead, there are two distinct worlds. Intelligence is no longer limited to biological forms (bio-intelligence) but now includes at least two diametrically opposed types—artificial intelligence (e-intelligence)—alongside various transient hybrid forms enabled by neuroscientists, which are creating new kinds of beings or entities, such as artificial life forms (Aberšek, 2023; Aberšek, 2020). Potential learning environments have also evolved dramatically, transitioning from Internet 1.0 (1989) to Internet 4.0 (2020–2022) (Pratschke, 2024). The educational process itself has transformed, shifting from conventional face-to-face education within school settings to complex blended models, with a parallel move from formal education to diverse non-formal approaches (Blended Education). The Net generation exhibits distinct goals, requires different motivational incentives, and learns, acquires, and processes information in fundamentally different ways, necessitating a shift from digital to generative pedagogy. Consequently, teachers face new challenges. In generative pedagogy, the teacher no longer interacts with technology merely as a tool (as in digital pedagogy) but rather as a "colleague" in the form of generative artificial intelligence (GAI).

Technological Change and Education

If we focus on the interactions between technology, society, and education, we must start from the fundamental starting point that the world is no longer one; there are two worlds, the physical and cyber worlds, which intertwine and complement each

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other (Aberšek, 2024a). At the same time, we must also emphasize that man is no longer the only intelligent being; artificial intelligence (AI) and physical forms based on it are increasingly appearing - cybernetic physical systems (robots), which increasingly take over from humans a part of his psychomotor activities (robots and other cyber-physical systems) and also cognitive activities (intelligent agents). Physical e-being exists in both the physical and non-physical cybernetic worlds. In contrast, a human can only exist in the physical world, and non-corporeal forms of e-beings exist only in the cyber world but are connected to the physical world with the help of IoT (Aberšek, 2024b; Aberšek, 2024c).

Society and Education

We are all-time travellers, experiencing constant change and gaining new experiences. As we do this, countless connections between nerve cells in our brains are recalibrated to accommodate these experiences. It is as if we are reassembling ourselves every day; we are maintaining a mental construct of ourselves in physical time. The glue that holds together our core identity is memory. Our travels are not limited to physical time. We also experience mental time travel because we visit the past through our memories and then travel to the future by imagining what tomorrow and the following year could bring. When we do this, we think of ourselves as we are now, remember who we once were, and imagine what we will be like. On this basis, let us analyze the research baseline (Kordigel Aberšek & Aberšek, 2020).

Waves of Technological-Social Change

In his book, The Coming Wave (Suleyman & Bhaskar, 2023), Mustafa Suleyman points out that the world is not ready for a wave of powerful new AI technologies. He identified the "problem of containment" and the negation of reality as challenging for our time. Suleyman was far from the first to use this thesis to describe the upheaval that follows the introduction of disruptive new technologies and their impact on society. Joseph Schumpeter used the term "creative destruction" for the latter to describe the dynamics of technological disruption that have driven the so-called waves of innovation in the modern era (McKraw, 2007). Each wave in the series is characterized by a set of technologies that were the leading technology of the era. The first wave (1785 to 1845) triggered the Industrial Revolution with the steam engine, the second wave (1845 to 1900) started the Second Industrial Revolution with electricity, and the third wave (1900–1950) continued the Third Industrial Revolution with the advent of the computer. As each wave of technological change came, the dynamics of creative destruction brought with it new ways of working, living, and education as an integral part of society, but it also destroyed some of what came before. Generation after generation of students, teachers, intellectuals, experts, writers, researchers, and creators were the driving force behind the creative knowledge economy of the time.

Furthermore, the fourth wave (1950–1990), which continued the Third Industrial Revolution, was the era of computing and electronics. It also marks the beginning of artificial intelligence as a field of research when the mission began to create intelligent machines, "thinking machines." Its goal was to create machines that could learn and use human language. Thus, the fifth wave (1990–2020) was the digital age, defined by the

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networks made possible by the invention of the Internet (1983) and the World Wide Web (1989) (Berners-Lee et al., 2001).

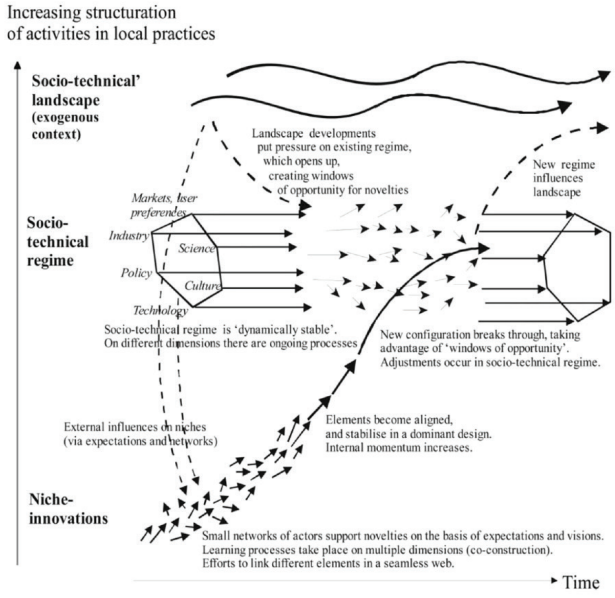
When the fifth wave began to decline, it was logical to continue into the sixth wave. In late 2015, OpenAI was founded by a group that worked to create a secure General Artificial Intelligence (AGI) for the benefit of humanity (Grace et al., 2024). In 2017, a team of Google researchers introduced a new type of transformer architecture (Vaswani et al., 2017) that enabled large language models (LLMs) to flourish in generative AI. (Radford & Narasimhan, 2018). By the end of 2023, the sixth wave had reached shore, and its creative and destructive effects were becoming increasingly apparent.

Generativity and Education

The gap in technological development between the AI industry and the school was more akin to a chasm, as the so-called AI gurus who had created their status overnight loudly proclaimed that the long-awaited "transformation" of education was imminent. In contrast, critical voices within the educational and academic world (pedagogical gurus) responded by refusing to consider its benefits and focusing solely on the harm. After 2022, when the company began to become aware of AI and LLMs, it was common to hear criticism responding to the relentless momentum of the AI industry. Meanwhile, in pedagogical academia, the wave of innovation was more akin to the curve of the Kübler-Ross cycle of grief (Kübler-Ross, 1969). This process began with shock and denial of the capabilities of AI, progressed to anger, followed by depression when these LLMs proved problematic, and finally, acceptance that generative AI (GAI) could remain, as schematically illustrated by Figure 1 (Flogie, Aberšek, 2019).

Figure 1

A Dynamic Multi-Level Systemic View on Socio-Technological Leaps Transition


Increasing structuration
of activities in local practices
Socio-technical' landscape (exogenous context)
Landscape developments put pressure on existing regime, which opens up, creating windows of opportunity for novelties
New regime influences landscape
Markets, user preferences
Socio-technical regime
Industry
Science
Policy
Culture
Technology
Socio-technical regime is 'dynamically stable'. On different dimensions there are ongoing processes
New configuration breaks through, taking advantage of 'windows of opportunity'. Adjustments occur in socio-technical regime.
External influences on niches (via expectations and networks)
Elements become aligned, and stabilise in a dominant design. Internal momentum increases.
Niche-innovations
Small networks of actors support novelties on the basis of expectations and visions. Learning processes take place on multiple dimensions (co-construction). Efforts to link different elements in a seamless web.
Time

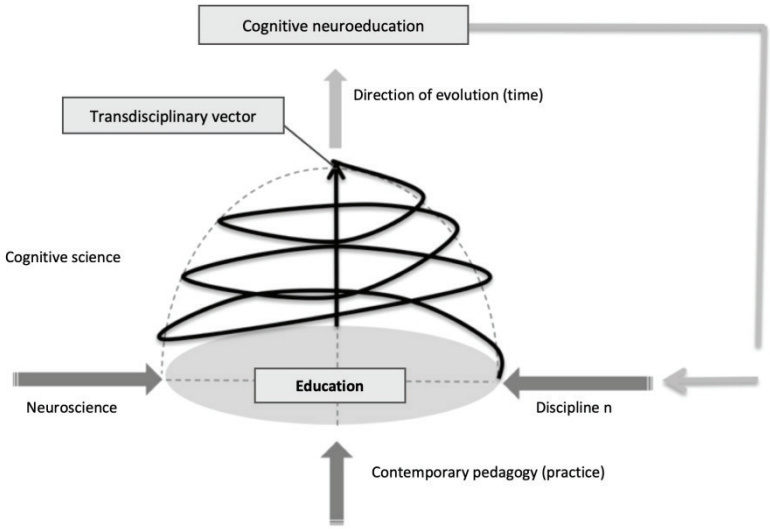
Source. Flogie & Abersek, 2019

Summing-up: What Does All This Mean for Education?

Web 4.0-based GAI is already significantly impacting our economies and political systems and will have an even greater impact on our cultures and ways of working. The exact form of these changes remains to be seen in the future. However, today's development will be extremely rapid and incomparable to any development in the past. The stakes will be exceptionally high for education, where the product is knowledge, and its engine is human intelligence. Artificial intelligence raises important questions about what knowledge is and, thus, about the value of the original transmitter/transmitter of knowledge, the teacher. Indeed, a new pedagogy will (must) be born, let us call it generative pedagogy, which will consider all these dynamic trends in the education field, symbolically illustrated by Figure 2 (Flogie, Aberšek, 2019).

Figure 2

Birth of a New Discipline: Cognitive Neuroeducation Based on Generative Pedagogy



Of course, we need to ask ourselves a few fundamental questions:

- What will be the role of the teacher in a world where GAI knows everything that we humans as a species have ever created, written, or shared?
- What is the value of producing educational content in a world where GAI can instantly recall anything taught or written?
- What is the value of assessment in a world where GAIs autonomously determine and perform their duties?

We do not yet have answers to these and many other questions that we do not even know (Pratschke, 2024). However, the shift in the value of creating, producing, and disseminating knowledge means that the role of the teacher will have to change

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drastically, and at the same time, GAI will no longer be treated just as a tool but as a partner. Regardless of the exact form or extent of the changes that are coming, we must prepare for a world in which people and GAIs operate in symbiosis, where the educator is no longer the only voice of authority but, for better or worse, one of many. The transition from today's, let us call it, digital pedagogy to the future generative pedagogy will be discrete, and it will be necessary to make a leapfrog transition, a quantum leap in an extremely short time (see Figure 1). Certainly, however, the teacher/person will no longer be the carrier of all knowledge; his role will increasingly move to the field of education, according to Bloom (1956), to the affective area, where he will become the carrier of the development of relationships and values.

Declaration of Interest

The authors declare no competing interest.

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A STEM APPROACH TO STANDARD SCIENCE CURRICULUM TOPICS: CHEMICAL REACTIONS AS A TYPICAL EXAMPLE

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Abstract

This study explores the integration of STEM principles into chemistry education through the redesign of the topic Chemical Reactions for initial teacher training. The aim was to develop and evaluate an innovative teaching module that fosters key competences–knowledge, skills, and attitudes—via student-centred, context-based, and interdisciplinary approaches. The research followed a design-based methodology, involving the development, implementation, and iterative refinement of teaching materials. Data were collected through textbook analysis, classroom observations, and pilot feedback from pre-service teachers. Key features of the module include experimental reaction cycles, real-life applications, and the use of digital tools. The findings show that this approach enhances students' conceptual understanding, motivation, and ability to connect chemistry with real-world issues such as sustainability and materials design. The module promotes inclusive and engaging science teaching and serves as a replicable model for other curriculum topics. It also supports the preparation of future teachers for competence-oriented and interdisciplinary education.
Keywords: *STEM education, chemical reactions, curriculum innovation, teacher education, experimental learning*

Introduction

Reforming the traditional curriculum in STEM subjects (science, technology, engineering, and mathematics) is essential to prepare students for a rapidly changing world in which these disciplines play a key role in addressing global challenges such as climate change, sustainability, and health innovation (Duncan, 2010). Modern education should reflect the interconnectedness of these disciplines and promote their practical application. It is essential to transcend traditional boundaries between subjects and enable students to understand the connections between theory and practice across disciplines. Integrating the teaching of mathematics, physics, chemistry, and technology opens up the space for deeper understanding and innovative thinking (Koldová et al., 2024).

At the same time, it is important to emphasise practical skills such as experimentation, working with data, or solving complex problems. Project-based learning and learning based on real-world challenges allow students to acquire the skills needed for today's job market. Creativity, teamwork, and critical thinking are just as important as professional skills today. Teaching approaches should therefore be oriented

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as much as possible towards actively involving students and encouraging them to think independently (Beers, 2011; National Academy of Engineering & National Research Council, 2014; Chroustová et al., 2021).

One of the standard topics in chemistry education that can be suitably transformed using STEM principles is chemical reactions. In the classical approach, these are often presented only as a set of equations or through isolated demonstrations. However, current teaching can enrich this topic with an engineering approach, effective experiments, practical tasks, and a wider overlap with everyday life. Such teaching enables students to better understand the mechanisms of chemical processes and, at the same time, develops their ability to apply the knowledge gained in new situations.

The aim of this study was to address this gap by developing and evaluating an innovative teaching module on chemical reactions designed for pre-service science teachers as one example of the results of the project Erasmus+ STEMkey (Teaching Standard STEM Topics with a Key Competence Approach) (STEMkey, 2023). The module incorporates experimental cycles, real-life applications, and interdisciplinary connections to foster key competences as defined in the European Framework. This paper presents both the theoretical foundations and practical outcomes of implementing the module in initial teacher education.

Research Methodology

General Background

This research is grounded in a design-based research (DBR) approach, which is well-suited for educational innovation and iterative refinement of teaching practices (Trna, 2011). The study focused on transforming the traditionally taught topic of chemical reactions into a STEM-based teaching module for pre-service chemistry and science teachers. The rationale stems from the need to align initial teacher education with current educational challenges, including sustainability, interdisciplinarity, and competence development. The study aimed not only to develop a pedagogically sound curriculum innovation but also to investigate its impact on teaching practices and student engagement.

Sample Selection

The research involved a purposeful sample of 8 chemistry teachers from the practice and 16 pre-service science teachers enrolled in a master's program at the Faculty of Education, Charles University, Czechia. These teachers were selected based on their active participation in chemistry methodology courses and their willingness to engage in curriculum development activities. The sample represents a typical population of future secondary school chemistry teachers in the Czech educational context.

Instruments and Procedures

The research process consisted of three main phases: (1) analysis of existing teaching practices, (2) design and implementation of the new module, and (3) evaluation and refinement based on feedback.

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1. Phase 1 – Needs Analysis
   A qualitative review of chemistry textbooks, curriculum documents, and lesson plans was conducted to identify how the topic of chemical reactions is currently taught. Classroom observations and informal interviews with teacher educators further informed the identification of common shortcomings, such as over-reliance on theoretical instruction and limited hands-on experimentation.
2. Phase 2 – Module Design and Implementation:
   Based on the initial findings, an innovative teaching module was developed. It included structured experimental cycles (e.g., the calcium cycle), real-life applications, interdisciplinary activities, and digital simulations. These elements were embedded in a sequence of learning tasks, scaffolded into three stages: warm-up, immersion, and real-life connection. The module was piloted in seminar settings over two academic terms.
3. Phase 3 – Evaluation and Feedback Collection:
   Teachers' feedback was gathered using interviews, and student future teachers' feedback was gathered using group discussions. Observations of student engagement and performance during activities also served as data sources. Revisions were made to the module after each round of implementation, ensuring it was responsive to user needs and aligned with pedagogical goals.

Data Analysis

Qualitative data were analysed using thematic coding to identify recurring patterns in teachers' and students' feedback and classroom interactions. Particular attention was given to indicators of conceptual understanding, motivation, and perceived relevance of the module. Reflective statements were categorized according to the European Framework of Key Competences, allowing the researchers to map evidence of competence development. Observational notes were used to triangulate self-reported data and validate the findings.

Research Results

The integration of the STEM approach into the topic of chemical reactions in initial teacher education aims to support the development of key competences, defined as a combination of applied knowledge, skills, and attitudes. This approach emphasizes student-centred learning, real-life applications, interdisciplinary links, and the use of digital tools. Through these principles, the teaching of chemical reactions is transformed into a context-based learning experience that reflects current societal and environmental challenges.

Within the proposed module, students explore the principles and consequences of chemical changes as a foundation for understanding natural processes. Central to the approach is the use of *experimental cycles*, where the starting and final substances are the same. These cycles highlight the interconnectedness of chemical processes, their classification, and their relevance to everyday life and sustainability.

Knowledge is acquired through hands-on activities, critical observation, and reflection. Skills are developed in three learning environments–*in vivo* (real-life

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context), *in vitro* (laboratory experiments), and *in silico* (digital simulations and models). These activities foster scientific inquiry, reasoning, and evidence-based decision-making. Attitudes are shaped by encouraging critical thinking, ethical reflection, and environmental awareness.

The proposed curriculum is structured into progressive stages—introductory ("warm-up"), exploratory ("immersion"), and applied ("real-life connection") activities. Students work individually and in groups, participate in discussions, and engage with experimental tasks designed to build understanding and support meaningful application of chemical concepts.

By integrating chemistry with other STEM disciplines—particularly mathematics, engineering, and digital technologies—students not only strengthen their conceptual grasp but also develop the ability to relate scientific content to real-world issues. The ultimate goal is to prepare future teachers to implement chemistry education in a way that is innovative, inclusive, and responsive to the demands of modern society.

For the ambience evocation, we propose a warm-up activity oriented to mapping the field of interest with the title "Chemical reactions and their use in sustainable development". This activity serves to mapping of elected types of chemical reactions in complex social problems – chemical reactions related to production, consumption, and sustainable development – in detailed different contexts. At the beginning of this activity, brainstorming is recommended (with the right setting, time, prohibited words, technical realization, etc.). Central term for brainstorming can be CHEMICAL REACTIONS or different types of chemical reactions or changes of substances, e.g., "REDOX REACTIONS" or "FERMENTATION", etc., or something other with relation to the topic Chemical reactions as self. The next step is clustering; it means the classification of groups of produced words. Students propose groups such as science, economics, politics, culture… The last step is the creation of concept maps in each group of words, and next to create a common concept map about the phenomenon CHEMICAL REACTIONS, connected with discussions about different experiences, mainly with everyday contexts. Notices for brainstorming topic alternatives can be more sophisticate, it means e.g. producing only conditions for chemical reactions (kind of substances, area of industry, agriculture etc.) or producing names or words containing the different word connected with chemical reactions (processes of production, chemical reactions and their examples in different languages etc.). Types of chemical reactions have different connections with other science disciplines and not only with them. A very wide impact have topics such as redox reactions and electricity, complex reactions and pigments, addition reactions and food production, acid-base reactions and volumetric analysis, etc.

For a deeper understanding of the topic Chemical Reaction, we pay attention to so-called reaction cycles in connection with STEM approaches under the title "Conversion of chemicals based on calcium compounds". The concept of experimental cycles meets the trends of increasing students' interest in a traditional and often uninteresting topic, not only by the sheer funny effect of the topic, but also by its interesting content and context. However, some very well-known experimental cycles (e.g., copper cycles) do not meet the requirements for the safety of the work in terms of their implementation in the school laboratory. A feasible experimental cycle seems to be the calcium cycle, which, although less convenient in terms of colour changes and the typology of chemical reactions, meets the safety requirements better and, on the other hand, has very close contacts with practical applications (building and construction materials).

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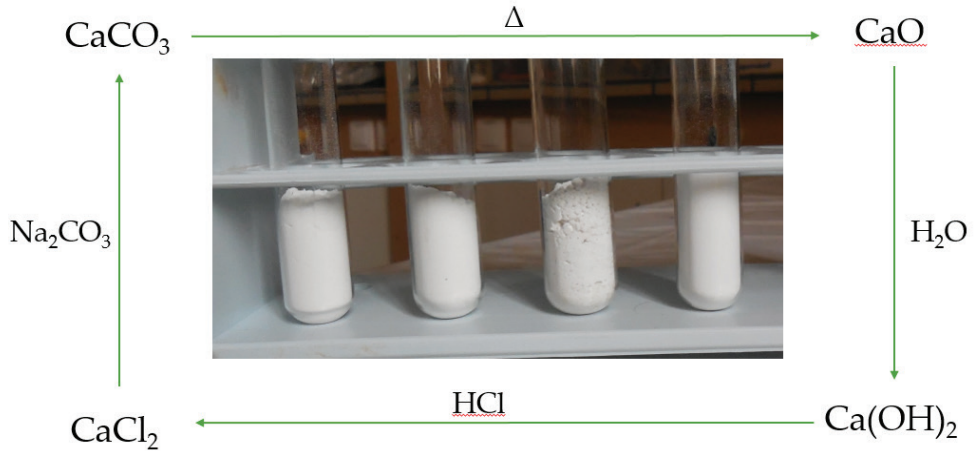
Although the experimental cycles of copper described above meet the requirements for a school chemistry experiment in terms of variability and description possibilities of chemical reactions, the situation is less favourable in terms of safety requirements. For these reasons, the experimental copper cycle can be replaced by the calcium cycle, which, although less favourable in terms of colour changes and also in terms of the typology of chemical reactions, better meets the safety requirements for its use in teaching. In general, information on the experimental calcium cycle can be found in various contexts. For example, the calcium cycle in nature or the process of limestone burning, lime quenching, and mortar solidification are well known in various forms, including practical contexts, especially in the construction and architecture. For the school laboratory, we can design an experimental calcium cycle based on chemical transformations associated with changes in state - solid white substances and colourless solutions. The experimental cycle includes different types of reactions, representing the chemical properties of calcium compounds, and shows the interrelationship of chemical transformations, characteristic of this element and other elements of the same group (e.g., magnesium). In this context, we propose to implement the cycle shown in Figure 1. It is a cycle consisting of four sub-steps:

1. Thermal decomposition of calcium carbonate
2. Reaction of calcium oxide with water
3. Reaction of calcium hydroxide with hydrochloric acid
4. Reaction of calcium chloride with sodium carbonate.

Figure 1
Experimental Calcium Cycle



Note: from left, calcium carbonate, calcium oxide, calcium hydroxide, calcium chloride (STEMkey, 2023)

The first two reactions represent chemical decomposition and chemical fusion, the next is an acid-base reaction, and the last is a precipitation reaction that leads to a product identical to the starting substance of the cycle. The cycle thus represents the major basic types of reactions of inorganic substances. The actual performance of the

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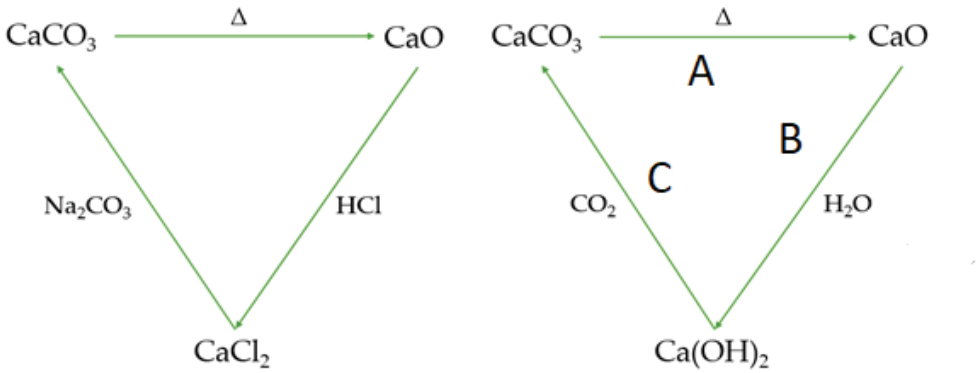
individual reactions is possible with basic chemistry laboratory equipment, even in elementary schools, and with available chemicals. The partial decomposition of calcium carbonate or the low solubility of calcium hydroxide in water, for example, should be taken into account when implementing a set of reactions, which can also be a stimulus for creative discussion. Simpler variants derived from the previous cycle are shown in Figure 2, which shows two cycles.

Figure 2
Basic Cycle Alternatives – Calcium



Note. STEMkey, 2023

The first one shows a set of reactions: thermal decomposition of calcium carbonate, reaction of calcium oxide with hydrochloric acid, and reaction of calcium chloride with sodium carbonate. This is a classic method of converting limestone to pure calcium carbonate (production of pure calcium carbonate for the cosmetics, food, and paper industries). The second cycle (the thermal decomposition of calcium carbonate, the reaction of calcium oxide with water, and the reaction of calcium hydroxide with carbon dioxide) focuses on a familiar theme - the burning of limestone (A), the extinguishing of lime (B), and the solidification of mortar (C). Each reaction is accompanied by a series of tests to demonstrate the presence of starting materials and products in the reaction mixture.

The cycle on the right side of Figure 4 directly links to various building materials, and its use in project-based learning is suggested. Thus, in the creation of different materials from concrete or mortar that can be used in the daily life of the school or its surroundings (see Figure 3).

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Figure 3

Examples of Concrete Outdoor Furniture as Products of a School Project Oriented to the Improvement of the School Garden

Source: https://www.tzb-info.cz/rozhovory-komentare/16072-betonove-designove-stoly-ve-skolni-zahrade-vznikly-diky-iniciative-rodicu

Experimental activity connected with the calcium cycle focuses on interdisciplinary connection mainly in project applications (concrete outdoor furniture, concrete art creations, mortar products, analysis, and using construction (smart) materials, etc.

Application tasks in the topic Chemical Reaction offer various examples from different areas of everyday life. One example deals with the engineering aspects of a funny experimental activity with the title "How to prepare material with specific properties?". The STEM appropriate way to teach chemical reactions is to show them in action and, based on the possibilities, let students get hands-on with exploring the reactions. One of the main questions concerning used materials is their properties. Hands-on activities nearby chemical reactions can provide students with these experiences. Students will define criteria and constraints for creating a new material as part of the engineering process, look for a change in properties to see whether a chemical reaction occurs, and a new substance is formed, and know that chemical reactions create new materials.

The preparation of new materials with specific properties involves chemical reactions based on different starting materials. A suitable funny example can be the so-called slime, which is often found in entertaining chemistry shows. The different properties of slime will require students to apply the engineering reasoning and design process to plan, create, and test their slime product. They will need to reason and decide

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on providing the desired properties of their slime and then experiment to find the most appropriate process for its preparation (recipe).

The activity will begin by identifying a suitable procedure to prepare the slime (some students can have an experience with slime creation). There are well-known procedures using the so-called "white school glue," or it is possible to use flour or other substances. Each procedure, which is best done in groups, is discussed with the teacher to ensure safety and availability of the necessary starting materials. The chemical principle of slime production is also discussed (crosslinking of polymers).

First, it is possible to vary the slime preparation procedure to obtain different slime products. For example, use a larger or smaller amount of one of the starting substances (e.g., contact lens solution if a procedure using it is used). A so-called "fluffy" slime can also be made, for example, by using an appropriate amount of shaving foam instead of water, etc. The next steps are focusing on preparing slime with specific properties. It can be e.g.: shimmering slime (adding glitter), magnetic slime (adding iron filings), glowing slime (adding glowing colour), slime changing colour based on temperature change (adding thermochromic pigment), glow-in-the-dark slime (adding e.g., tonic drink), slime reacting to the pH of the environment (adding an acid-base indicator, e.g., red cabbage juice), etc.

Production of materials with different properties is one of the main objectives of engineering activity or engineering thinking. In connection with the phenomenon, chemical reaction is an important example of STEM education. Chemical reaction, physical condition for realisation, and different next connections as biological, mathematical, or environmental, have to be in account.

Figure 4

Samples of Slime as the Products of STEM-Oriented Chemical Experiment at Elementary School

Source: https://staryweb.zsnizbor.cz/clanky/art/58/34/SLIZ-ve-skole

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Discussion

The findings of this study suggest that integrating a STEM-based approach into the teaching of chemical reactions significantly enhances pedagogical outcomes in initial teacher education. In particular, the use of experimental cycles and context-rich, interdisciplinary activities promotes conceptual understanding, learner engagement, and competence development across cognitive and affective domains (Rychtera & Bílek, 2018; Vondrová & Rendl, 2015).

These results align with previous research emphasizing the benefits of inquiry-based and context-oriented teaching in science education. For example, the work of Trna (2011) and the National Research Council (2012) highlights the importance of connecting scientific content with real-world applications to improve students' motivation and relevance perception. The current study builds upon these foundations by offering a specific and replicable model of how such integration can be implemented in chemistry teacher training.

The use of experimental cycles, such as the calcium cycle, is especially noteworthy. While previous studies (e.g., Condike, 1975; Todd & Hobey, 1985; Walker et al., 2012) have shown the educational value of reaction cycles like the copper cycle, our research contributes by identifying and testing a safer and more applicable alternative for classroom use. The calcium cycle not only maintains the pedagogical strengths of circular processes (Duesing, 1985; Luna Vera et al., 2018; Royal Society of Chemistry, 2015) but also better meets safety and feasibility criteria, as discussed in the work of Kolář et al. (2018; 2019).

Moreover, the structure of the teaching module—scaffolded into warm-up, immersion, and real-life connection phases—supports diverse learning styles and reinforces the pedagogical principles of differentiation and inclusion (Beers, 2011). These aspects are consistent with contemporary approaches that emphasize student agency, collaboration, and creativity in STEM learning (National Academy of Engineering & NRC, 2014).

In contrast to traditional instruction methods, often criticized for their abstractness and limited transferability (Rychtera & Bílek, 2018), this study shows that curriculum innovation grounded in STEM integration allows for the transformation of even conservative topics into engaging and meaningful learning experiences. The inclusion of "in vivo", "in vitro", and "in silico" components further supports multimodal learning and reflects broader pedagogical trends aimed at blending hands-on, experimental, and digital learning environments (Chroustová et al., 2021).

In terms of theoretical contribution, this study offers a concrete example of how competence-based education frameworks (COM, 2019) can be operationalized in subject-specific teacher training. By integrating practical applications, ethical reflection, and interdisciplinary connections, the module fosters the development of transversal competences that are increasingly demanded by modern education systems (Schneider, 2016; STEMkey, 2023).

In summary, the present study not only confirms findings from earlier research but also extends current knowledge by providing a systematically designed, evaluated, and adaptable model for chemistry education within the STEM paradigm. It serves as a bridge between theoretical recommendations and practical implementation in teacher education, offering guidance for future curriculum development and educational policy.

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Conclusions and Implications

The findings of this study confirm that the implementation of a STEM-based approach to the standard taught topic of chemical reactions can bring significant improvements to initial science teacher education. Through curriculum innovation grounded in design-based research, we have developed a model that supports deeper conceptual understanding, engagement with real-world issues, and development of transversal key competences. The use of experimental cycles, context-based learning and interdisciplinary integration has proven to be both pedagogically effective and practically feasible in school settings.

One of the most important implications of this work is the confirmation that even traditional topics, often perceived as abstract or difficult, can be transformed into engaging learning experiences. By applying inquiry-based methods, incorporating real-life applications and allowing space for student creativity, future teachers are better prepared to address the diverse needs of their students and to support their development as active, competent, and responsible citizens.

The proposed teaching module can serve as a replicable model for the redesign of other curriculum topics in chemistry and beyond. The integration of "in vivo", "in vitro," and "in silico" approaches illustrates the flexibility of the STEM framework in accommodating different learning styles and technological opportunities. This adaptability is crucial for modern classrooms, which require both innovation and inclusivity.

Furthermore, the results indicate the importance of preparing future teachers not only in subject content, but also in pedagogical strategies that are in line with contemporary educational challenges, such as sustainability, digitalisation, and interdisciplinary problem solving. Embedding these elements into teacher education ensures that graduates are ready to implement forward-looking and meaningful science teaching in their future careers.

The presented approach contributes to bridging the gap between academic science education and practical teaching demands. Its broader application could foster a more integrated, responsive, and competence-oriented model of STEM education that is aligned with the societal expectations of the 21st century.

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Declaration of Interest

The authors declare no competing interest.

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DEVELOPMENT OF THE CONTENT OF THE "BIOLOGY I" SET OF METHODOLOGICAL MATERIALS FOR A COMPETENCE-BASED APPROACH TO SECONDARY SCHOOL BIOLOGY

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Abstract

The competence-based approach has raised important questions in education regarding the content of learning, the way teachers teach and students learn, and the assessment of learning. General education in Latvia has been reformed, and the content of competence-based education was introduced in 2023. In STEM curricula, the content is developed in the context of the Big Ideas, and the number of teaching hours is restructured. Only 105 teaching hours are foreseen for biology at the optimal secondary level, which is twice less than before. So, it was important to learn how this approach is implemented in the biology content to achieve learning outcomes defined in the Latvian secondary education standard, what opinion of biology teachers is on the content of Biology I curriculum developed by Skola2030, and what the content of the biology methodological material should be. Through mapping of learning outcomes and the survey of biology teachers, the main problems were identified: insufficient number of lessons, illogical sequence of topics and subtopics, and lack of teaching resources. On this basis, a set of Biology I methodological materials was developed.
Keywords: *biology education, content of secondary school curriculum, integration of Big Ideas, set of methodological materials, competence-based approach*

Introduction

The competence-based approach (hereafter in the text – CBA) to education changes traditional learning paradigms by emphasising the development of knowledge, skills and attitudes to deal with real-life situations (Biesta, 2009). It aims not only at providing theoretical knowledge, but also at developing practical skills and attitudes needed in today's society. The curriculum should focus on developing students' skills and abilities, not just on imparting knowledge. The curriculum content is an essential component of education as it determines what knowledge and skills students will acquire, as without a conceptual base students cannot innovate (Wiggins & McTighe, 2005), and the standardisation of content ensures equity between educational institutions by allowing for objective assessment of competency performance (Hattie, 2009; OECD, 2018). Structured content guides educators by reducing the need to create materials themselves, which is particularly important for new teachers (Darling-Hammond et al.,

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2020). However, ambiguity in the curriculum can hinder teachers' work (Amadio et al., 2014), and a too rigid focus on content can lead to the mechanical reproduction of knowledge rather than its application.

Biesta (2009), describing the three functions of education as qualification, socialisation, and subjectification, warns that the CBA can degrade education into functional skills training if the content is seen as an end in itself. The overload of new content elements without getting rid of old ones can increase the time spent learning topics, leaving less time for the practical application of competences (Voogt & Roblin, 2012; Priestley & Sinnema, 2014).

Curriculum content is essential for implementing a CBA in STEM subjects, providing theoretical foundations, practical skills, and interdisciplinary thinking (Bybee, 2013). In biology, it builds an understanding of life processes and their interrelationships. Teachers face both advantages and challenges in implementing the competence-based approach.

The main advantage of the CBA is the focus on students' ability to apply knowledge in real-life situations. In biology, this means applying theoretical knowledge, for example, in experiments or in the analysis of ecological problems. It also promotes the integration of subjects, such as working together with chemistry, physics, and mathematics to develop a holistic understanding of science (Krauss, 2024). Furthermore, it allows for the tailoring of the curriculum and methods to the needs of each student, promoting individual growth (Tomlinson, 2014).

The main challenge of the CBA is the increased investment of teachers' time and resources (Hattie, 2009). In biology, this means additional laboratory equipment and experiment time. It requires teachers to acquire new skills and professional development (Darling-Hammond, 2010), especially the acquisition of new pedagogical methods and the integration of curriculum with other STEM disciplines. Competency assessment can be more complex compared with the traditional methods, as not only knowledge but also skills and attitudes need to be assessed (Black & Wiliam, 1998).

In Latvia, the introduction of the CBA started in 2016 with the European Social Fund project "Competence-Based Approach in the Curriculum" implemented by the National Centre for Education Content. The aim of the project was to develop and implement a curriculum that promotes students' ability to apply knowledge in practice by developing critical thinking, problem-solving skills, and creativity. Existing curricula were reviewed to reduce fragmentation and to enhance students' ability to apply knowledge to real-life situations. Seven areas of learning were identified: language; social and civic; cultural awareness and self-expression in the arts; science; mathematics; technology; health, safety, and physical activity. For each of these areas, learning outcomes and model curricula were developed that integrate the eight transversal competences: self-directed learning, critical thinking and problem solving, creativity and entrepreneurship, collaboration and civic engagement, and digital literacy (Skola2030, 2019). There are three levels of learning in any subject area in secondary education: the general level of learning, the optimal level of learning, and the highest level of learning.

The number of teaching hours was also changed for science subjects. The previous, still valid, standard for general secondary education provided for the same number of hours (210) for the subjects of biology, chemistry and physics, but the new concept provides for twice as few hours for the subject of biology (105 hours; compared to 245

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for physics and 210 for chemistry) (Ministru kabinets, 2019). The school can implement this curriculum in one academic year with 2 lessons per week and in 1.5 academic years with one lesson per week.

The content of the STEM subject curriculum was developed based on the Big Ideas (Harlen, 2015), including 10 big questions taught separately in biology, physics, chemistry, and geography, and big questions to be taught together (Table 1). Big questions 7-10 are covered in biology as a separate subject.

Table 1

Integrating Big Ideas Themes into Science Subjects

Big Questions acquired in separate subjects	Big Questions taught together
1. All matter in the Universe is made of very small particles 2. Objects can affect other objects at a distance 3. Changing the movement of an object requires a net force to be acting on it. 4. The total amount of energy in the Universe is always the same, but it can be transferred from one energy store to another during an event 5. The composition of the Earth and its atmosphere and the processes occurring within them shape the Earth's surface and its climate 6. Our solar system is a very small part of one of billions of galaxies in the Universe 7. Organisms are organised on a cellular basis and have a finite life span 8. Organisms require a supply of energy and materials for which they often depend on, or compete with, other organisms 9. Genetic information is passed down from one generation of organisms to another 10. The diversity of organisms, living and extinct, is the result of evolution	11. Science is about finding the cause or causes of phenomena in the natural world 12. Scientific explanations, theories, and models are those that best fit the evidence available at a particular time 13. Applications of science often have ethical, social, economic, and political implications

The SCAP assessment system is used in education in Latvia. This system helps teachers to assess students' learning outcomes and give feedback on their progress. The SCAP assessment system consists of four levels (Table 2).

- Starting to acquire (S): Indicates that the learner has begun to learn the content but has not yet achieved sufficient understanding or skills.
- Continuing to acquire (C): Indicates that the learner is continuing to learn the content and has made progress, but has not yet fully acquired the required knowledge and skills.
- Acquired (A): Indicates that the learner has mastered the content and demonstrates sufficient understanding and skills.
- Proficient (P): Indicates that the learner has mastered the content in depth and demonstrates a high level of understanding and skills.

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Table 2
SCAP Assessment System

	Starting	to acquire	Continuing to acquire	Acquired	Acquired proficiently
Points	1–2	3–4	5–6	7–8	9–10
Percentage	0–20 %	21–40 %	41–66 %	67–86 %	87–100 %

Research Problem

In today's education system, the CBA has become a priority to prepare students not only for acquiring knowledge, but also for applying it skillfully in real-life situations. Biology, as a branch of science, provides many opportunities to develop critical thinking, problem-solving skills, and collaboration, which are essential aspects of the competence approach. Despite educational reforms and the introduction of new teaching approaches (OECD, 2018), teachers and students still face difficulties in applying the CBA effectively to learning biology. This leads to a situation where students do not always develop higher-level thinking skills and are unable to apply knowledge to real-life situations. OECD PISA data show that Latvian students' performance in science is average or below average compared to other countries (OECD, 2019), indicating a need to improve analytical and problem-solving skills. Developing the curriculum content in a CBA can be a challenge, as existing content and teaching methods often do not meet modern educational requirements and students' individual needs (Skola2030, 2019), so it is important to review the Skola2030 biology content and involve the content implementers - biology teachers - in its evaluation.

Research Focus

In Latvia, the content of competence-based education was fully implemented in general education in 2023. The curriculum reform has marked a shift in teaching and pedagogical approaches (OECD, 2020). In 2023, a set of methodological materials was developed within the framework of the European Social Fund-funded project "Support for the Development of Individual Competences of Learners" (No 8.3.2.2/16/I/001) sub-project "Digital Authoring Solutions for the Development of Learning Strategies for STEM Content Learning to Mitigate the Impact of Pandemic (Biology I)" (Identification No VISC 2023/2). In collaboration with the academic staff from the Faculty of Biology (now Faculty of Medicine and Life Sciences) of the University of Latvia and practising teachers, a restructured alternative Biology I curriculum was developed, covering seven topics relevant to the Education Standard of Latvia and the Big Ideas, and 105 lessons were developed. All developed teaching materials were uploaded to the authorised website Skolo.lv, and biology teachers have access to it. According to the current portal data (25.02.2025), the resource has 456 users.

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Research Aim and Research Questions

In order to create a set of methodological materials that would meet the needs of teachers, it was necessary to study the content and relevance of the Biology I curriculum developed by Skola2030, as well as to find out teachers' opinions on the implementation of the curriculum in school. The aim of the study was to investigate how the CBA is implemented in the Biology content. To do this, a number of research questions were set:

1. To what extent does the Biology I curriculum developed at Skola 2030 meet the outcomes set out in the Latvian Secondary Education Standard?
2. What are the opinions of biology teachers on the content of the Biology I curriculum developed by Skola2030 in the context of the competence-based approach?
3. How and what was the content of the Biology I methodological materials developed in order to achieve the learning outcomes set in the Education Standard of Latvia?

Research Methodology

General Background

In order to answer the question to what extent the model Biology I curriculum developed by Skola 2030 meets the outcomes set out in the Education Standard of Latvia, the mapping of learning outcomes was performed. All the outcomes included in the topics were mapped against the outcomes set in the standard. Subsequently, a content analysis was performed to determine whether the full achievement of the outcomes set out in the standard is expected, and to identify issues that do not appear in the list of curriculum outcomes.

In order to find out how the model Biology I curriculum developed by Skola2030 is implemented in schools, a survey was carried out with the participation of secondary school biology teachers in Latvia. Based on the survey of teachers' opinions, an alternative set of Biology I methodological materials for teachers was developed.

Sample

A survey of biology teachers was conducted in 2023 and 2024. 97 biology teachers from Latvian gymnasia (28%) and secondary (72%) schools participated in the survey (length of service: 1/2-10 years - 23.3%; 11-20 years - 17.1%; 21-30 years - 29.5%; 31-45 years - 21.9%). Of these, 11% were male and 89% female, with the majority (49%) aged between 51 and 65 years. The teachers surveyed represented schools in Riga City (43.2%), urban schools in the municipalities (33.8%), public schools in the cities (12.9%), and schools in rural areas (10.1%).

Instrument and Procedures

The mapping was carried out using the General Secondary Education Standard of Latvian Cabinet of Ministers Regulation No 416, Annex 5 (Cabinet Regulations...,

https://doi.org/10.33225/BalticSTE/2025.30

2019), the content for the Optimal Level of Learning and Biology I: Model Curriculum for the General Secondary Education (Biology I.., 2019)

The questionnaire was structured in two parts (Figure 1). The first part elicited information on the respondent's profile (sex, age, type of school, length of service, and subject taught). In the second part, respondents answered 10 closed-ended (Q7.1-Q7.10) Likert scale questions on a 5-point scale (1 = strongly disagree, 5 = strongly agree) and 3 open-ended questions. The closed-ended questions assessed the School 2030 Biology I curriculum in the context of the CBA, focusing on the relevance of the curriculum content to the core principles of the competence-based approach.

Figure 1

The Structure of the Questionnaire

Profile of the respondent	Content of the model programme
Gender Age School type School location Years of experience Subject	**1.** 10 closed-ended Likert scale questions (Q7.1-Q7.10) on the aim of the programme, the outcomes to be achieved, the number of lessons, the topics, their arrangement and sequence **2.** Four open-ended questions (Q8, Q9, Q10, Q11) on the content, problems in learning the topics and suggestions for solving them

The survey was hosted on the *QuestionPro* e-platform and initially used a snowball method to engage respondents. The link to the survey was then placed on the Skolo.lv website accessible to teachers next to the created set of Biology I methodological materials.

The teacher survey on the content of the model Biology I curriculum developed by Skola 2030 asked four open-ended questions: Q.8. Another answer (supplement to questions Q7.1-Q7.10). Q9. About the content of the Programme, I can say that ... (positive/negative opinion, reasons for it). Write your answer; Q10. I have difficulties in teaching certain topics (Write your answer, indicating the topic and the problem. If there are no difficulties, indicate NONE); Q11. What should be done to eliminate these problems?

Data Analysis

Mapping the learning outcomes to be achieved. All the expected student learning outcomes at the optimal level in the subject of Biology standard were mapped in an Excel file. Then, all the outcomes defined in the model topics of the Biology I programme were mapped against them, according to the reference to the corresponding outcome of the standard. A content analysis was then carried out to determine the relevance by assigning the following labels to the standard outcomes: fully covered, partially covered, and not included in the curriculum. The results, together with the conclusions on the identified gaps, were shared with the developers of the methodological materials so that the gaps could be addressed in the development of the materials.

https://doi.org/10.33225/BalticSTE/2025.30

Analysis of survey data. Descriptive statistics (Mean and Standard deviation), Cronbach's alpha were used to assess the internal consistency of the survey. It was found that the questions had high consistency ($\alpha = 0.945$). As the data were not normally distributed and the sample size was small ($N = 97$), non-parametric statistical methods were used.

In order to find out what the content of Biology I methodological materials should be in order to achieve the learning outcomes set out in the Education Standard of Latvia, teachers' answers to open-ended questions were collected, and an alternative set of Biology I methodological materials was created. The developed teaching materials were mapped to the learning outcomes to confirm their compliance with the Education Standard of Latvia.

Research Results

Mapping the Learning Outcomes to be Achieved

The mapping and content analysis showed that 24% of the deliverables indicated in the Standard are fully covered, 41% are partially covered, and 35% of the deliverables are not included in the curriculum. An example of the mapping and content analysis of one of the Standard's deliverables is shown in Table 3.

Table 3
An Example of the Mapping of One of the Learning Outcomes Set in the Standard

Learning outcome set in the standard	The learning outcome defined in topic 2, referring to the specific learning outcome of the standard	The learning outcome defined in topic 4, referring to the specific learning outcome of the standard	Conclusions and necessary improvements
9.1.2. Explains the causes of genetic diversity using a variety of information about fertilisation, the results of cell division, and their role in nature, using the terms gene, DNA, chromosome, mitosis, meiosis, zygote, haploid, diploid	Explains the importance of the processes of mitosis and meiosis in nature by studying root tip cell division under a microscope, calculating the number of chromosomes in the germ cells of different organisms, inferring the process of sex determination, the process of pregnancy, structuring and analysing information. (D.O.7.4.1.; D.O.7.4.2.; D.O.7.1.1.; D.O.9.1.2.; D.O.11.2.1.)	Constructs a family tree using common symbols to predict the diversity of individuals based on a characteristic feature. (D.O.9.1.1.; D.O.9.1.2.; D.O.11.2.3.; D.O.11.3.1.)	The programme outcomes need to be extended to ensure that the student can explain the causes of genetic malformation and that all the concepts in the standard are covered

https://doi.org/10.33225/BalticSTE/2025.30

Survey Results

Using the quantitative and qualitative data from the survey, the main teacher insights into the content and implementation of the model programme were identified.

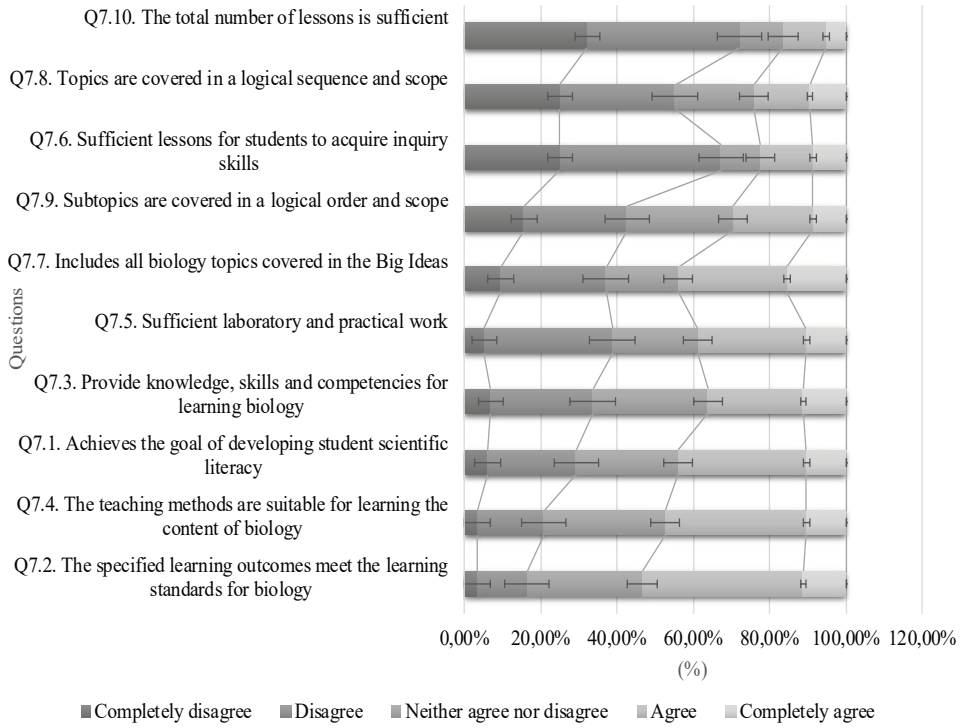
Evaluation of the Biology I programme developed by Skola2030

As shown in Figure 2, the highest mean score was given to Q7.2 on the achievement of the learning outcomes that meet the educational standard (M = 3.44, SD = 0.975), thus achieving the goal of building scientific literacy (Q7.1) (M = 3.18, SD = 1.098), as well as the appropriateness of teaching methods for learning biology (Q7.4) (M = 3.36, SD = 0.975).

The lowest ranked aspect of the curriculum content was the insufficient number of teaching hours (Q7.10) (M = 2.18, SD = 1.156), which also affects the development of students' research skills (Q7.6) (M = 2.40, SD = 1.241). The insufficient sequence and scope of sub-topics (Q7.9) (M = 2.82, SD = 1.187) was found to cause problems in the logic of content implementation (Q7.8) (M = 2.55, SD = 1.272), yet the programme covers all topics included in the Big Ideas (Q7.7) (M = 3.12, SD = 1.255).

Figure 2

Teachers' Views on the Content of the Curriculum Developed by Skola2030 and Its Implementation


Q7.10. The total number of lessons is sufficient
Q7.8. Topics are covered in a logical sequence and scope
Q7.6. Sufficient lessons for students to acquire inquiry skills
Q7.9. Subtopics are covered in a logical order and scope
Q7.7. Includes all biology topics covered in the Big Ideas
Q7.5. Sufficient laboratory and practical work
Q7.3. Provide knowledge, skills and competencies for learning biology
Q7.1. Achieves the goal of developing student scientific literacy
Q7.4. The teaching methods are suitable for learning the content of biology
Q7.2. The specified learning outcomes meet the learning standards for biology
Questions
0,00% 20,00% 40,00% 60,00% 80,00% 100,00% 120,00%
(%)
Completely disagree
Disagree
Neither agree nor disagree
Agree
Completely agree

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Overall, the mean scores for these questions range from the lowest arithmetic mean (M = 2.18) for Q7.10 to 3.44 for Q7.2. The lowest scores are for the number of teaching hours, indicating the need to increase both the total and the number of practical lessons. The largest standard deviations (SD > 1.2) are for Q7.6, Q7.7 and Q7.8, showing considerable variation in responses between respondents.

The open-ended survey questions were analysed to elicit teachers' perceptions of content aspects. In general, teachers identified a variety of problems, which can be grouped into 1) insufficient number of lessons, which makes it difficult to learn the content in depth and more qualitatively; 2) difficulties in teaching specific topics such as ecology, cell reproduction, immunity and DNA secrets; 3) chaotic programme structure - topics and sub-topics are not logically arranged; 4) lack of materials and methodological support: teachers have to create their own teaching materials, as outdated or insufficient content is offered, and often in topics where teaching materials are lacking, discussions or group work is offered; 5) confusion about the depth and breadth of topics to be covered by students; and 6) insufficient preparation of students, as they have not acquired sufficient background knowledge from studying biology in primary school.

The aggregated teacher responses on the content of biology can be found in Table 4.

Table 4

Assessment of the Biology I Content

Topic	Teachers' comments (quotes from teachers' responses)
1. Environment and evolutionary change in organisms	If biology is not taught in Grade 10, it is very difficult to work in Grade 11, because students remember very little. Chaotic planning. Basic questions are not acquired, but students are forced to make deep judgements about processes in nature. According to the new approach of School 2030, students in primary school have not learnt about the diversity of plants and animals, so it is very difficult to work on this topic, because you cannot teach ecology without learning about the systematics, anatomy, morphology of plants and animals as well as other organisms. It is very difficult to plan and carry out project work: a field study with 1 hour per week! It is not realistic to carry out the interdisciplinary project "Water", because there are no relevant topics in other subjects at this time.
2. Cell reproduction	It is difficult to talk about cell reproduction and the secrets of DNA without first learning about the structure of the cell. Artificial insemination - there is a lack of material in a language that young people can understand. No information on new research, developmental trends, real use.
3. The secrets of DNA	The chemical composition of the cell is not included. I additionally teach the chemical composition of the cell before the secrets of DNA. The information on the latest biotechnological developments is 10 years old.

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Topic	Teachers' comments (quotes from teachers' responses)
4. The inheritance of traits	There is no difficulty in presenting the topics, but the order is not clear, so I change places. Students who have not chosen to study biology in depth lack motivation to learn, so it is difficult to understand how much depth is needed, and there are not enough lessons to cover the topic sufficiently.
5. Immunity of the organism	No information on newer research - immunity, allergies, GMOs, cloning, transplantation, etc. It takes a very, very long time to find quality information, compile it and create a lesson. Lack of materials, lots of extra work, having to find the information yourself (immunity, endocrine system). Wherever there is a lack of information - the programme suggests using discussion, mind maps or group work, but I need to be able to supplement and explain with real, relatively recent examples (not 10 years old) from medicine or agriculture.
6. Cells and organism functioning	The sequence of topics is not clear at all - why is cell structure at the end of the programme, how can one learn about cell division and genetics without knowing it? Too few lessons. More lessons are needed for the whole programme. Illogical continuation of the subject of immunity. Some of the outcomes and content are duplicated in Biology II. Very little coverage of the functioning of the body. It is intended to be taught extensively and in a complex way in primary school, but it is difficult for students of this age to understand many of the issues. There is a lack of order in the sequence of topics, e.g., students learn protein synthesis and only then the components of the cell.

Development of the Set of Methodological Materials Biology I

Based on the teacher survey and the recommendations of the project team, an alternative Biology I curriculum was developed. The curriculum included other topics and sub-topics, a different sequence of topics, and a different number of lessons (Figure 3). The first topic *Cell - the basic structural unit of an organism* combined information from topics 3 and 6 (Skola 2030), the second topic *Reproduction of cells and organisms* included information from topics 2 and 6 (Skola 2030), topic 4 *Metabolism of cells and organisms* - topic 6 (Skola 2030), topic 5 *Genetic modification and biotechnology* - fragments from topics 3 and 4 (Skola 2030). Themes 3, 6, and 7 remained unchanged in terms of the number of lessons, but not in terms of content.

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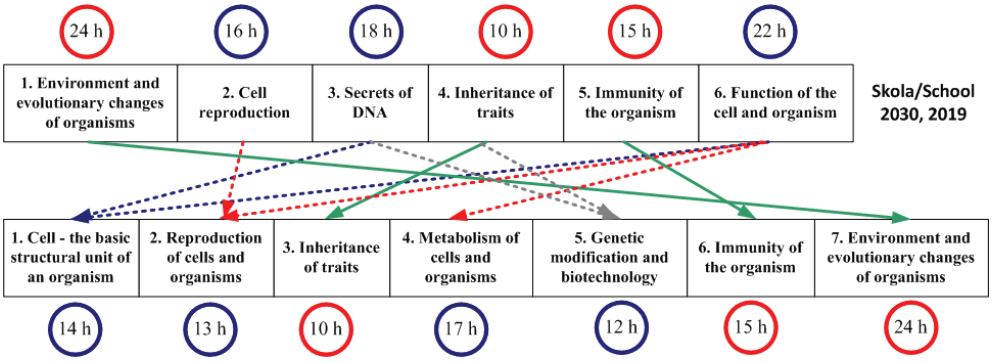
Figure 3

School 2030 Comparison of Biology I Model Curriculum and Biology I Methodological Materials



For each topic, the appropriate number of lessons was developed, following the same lesson structure: the title of the lesson, its place in the topic and subtopics, the lesson outcome (standard and lesson outcome), evidence of the achievement of the outcome, the transversal competences, a list of resources needed for the lesson, a lesson description with activities for both the student and the teacher to do during the lesson with a suggested time plan for each activity, possible additional resources that could be used in the lesson. The lesson was supplemented with a methodological commentary on the lesson, explaining why the lesson was designed in the way it was, the possibilities to modify and adapt the lesson to the teacher's own needs, and other valuable notes.

Supplementary materials were added to most of the lessons:

- student worksheets in editable and printable formats with solutions and methodological comments;
- lab reports in editable and printable format with methodological comments;
- final assignments in two versions in editable and printable formats with solutions and evaluation criteria, as well as methodological comments;
- other materials (videos, presentations, games).

The mapping of the learning outcomes was carried out during the development of the materials, thus ensuring that all outcomes are included in the resource. Four teacher workshops were held during the development of the materials, during which the lessons developed were evaluated. After the evaluation, 29 lessons were piloted in eight schools.

All the materials (Bioloģija I.., 2023) developed for teachers are available on skolo.lv, the authorized free virtual learning platform for teachers and students.

Discussion

The European Social Fund project "Competence-based approach in the curriculum" (Skola2030, 2019) aimed at developing and implementing a modern, competence-based curriculum from pre-school to secondary school. The development of the Biology I curriculum for the optimal level of secondary school posed significant challenges, as the reduced 105 teaching hours had to include extensive Big Ideas-based content: out of 10 different big questions, four questions were dedicated only to the subject of biology,

while the remaining 6 were dedicated to physics, chemistry and geography. As the teacher survey (Figure 2, Table 4) showed, the main difficulties were: 1) the insufficient number of lessons, which makes it difficult to cover the content in a deeper and more qualitative way; 2) the teaching of certain topics, such as ecology, cell reproduction, immunity and the secrets of DNA; 3) illogical sequencing of topics and sub-topics; 4) lack of materials and methodological support; 5) confusion about the depth and breadth of topics to be covered by students; 6) insufficient preparation of students.

Insufficient number of lessons makes it difficult to learn content in depth and more qualitatively. Research shows that more lessons are directly related to better student achievement (Mullis, et al., 2020), as teaching requires sufficient time for students to understand complex processes and concepts (Anderson & Krathwohl, 2001). Harlen and Qualter (2004) highlight that lack of time in STEM subjects leads to superficial content learning, resulting in students not developing critical thinking and problem-solving skills, which reduces the likelihood of building lasting knowledge (Darling-Hammond et al., 2020). Lack of time in biology lessons prevents teachers from engaging students in laboratory work, experiments, or discussions.

Difficulties in learning specific topics often require abstract thinking. Smith et al (1994) found that students associate ecological concepts only with theory rather than real-world application. This suggests the need to strengthen the link between theory and practice. Students also often have misconceptions about biological processes, which require additional time to clarify (Dauer & Long, 2015). Topics on cell reproduction, immunity, and the mysteries of DNA also require specific approaches and resources for students. As Tibell and Rundgren (2010) point out, difficulties have been reported in molecular biology regarding various aspects of genetics, cell structure and function, macromolecular structure, cell metabolism, and biophysical concepts.

Thus, there is a need for more structured explanations and multimedia integration in the learning of biology, which in turn requires learning materials and methodological support. The lack of materials and methodological support is a significant problem, as it increases teachers' workload if they lack accessible resources (OECD, 2019). This problem is also relevant in the Latvian education system (Birzina et al., 2023). In fact, the lack of teaching materials should be seen in a much broader context, starting from printed teaching materials, then digital ones, and finally reaching laboratory equipment (Sayan & Mertoglu, 2020). Materials developed by teachers themselves may often not meet the educational standard, and inadequate teaching materials may not always ensure systematic learning of the content.

A chaotic curriculum structure creates difficulties for both teachers and students if it lacks coherence and depth (OECD, 2019). In biology, the main difficulty is to relate different concepts at the cellular level and at the organism level (Verhoeff, et al., 2008). If topics (cell division) are taught before basic concepts (cell structure) in the biology curriculum, this leads to knowledge fragmentation. The competence-based approach requires a modular structure in which concepts are developed gradually. Uncertainty about the depth and breadth of topics affects the learning process. Education reform research (Hattie, 2009) shows that clearly defined goals and expectations are important for students' success. Lack of guidelines on the level of detail to be covered in specific topics creates problems in the curriculum implementation, so clearly defined objectives and benchmarks are essential to ensure that all students have the opportunity to acquire

https://doi.org/10.33225/BalticSTE/2025.30

the necessary competences. Vagueness contributes to superficial learning of content (Meyer et al., 2014).

Students' lack of preparation makes it difficult for them to learn biology at secondary school. Without a solid background, the content of the secondary school biology curriculum can become very challenging for students, as evidenced by the research of Eija et al. (2017) on the importance of systematics knowledge in primary education. Good background knowledge motivates students to learn biology (García-Pérez, & Peñaloza, 2025) and promotes understanding of biology when learning is linked to a context-based and science-technology-society approach (Bennett, 2007). Research on student success in higher education (Birzina et al., 2019; Binder et al., 1019) shows that students with lower prior knowledge at school, compared to students with higher prior knowledge at school, are unable to bridge the knowledge gap in the first year of university without further support.

Conclusions

The mapping of the learning outcomes made it possible to assess the extent to which the model Biology I curriculum developed by Skola 2030 meets the outcomes set out in the Education Standard of Latvia. The content analysis of the mapping of learning outcomes determined whether all the learning outcomes set out in the standard are included in the learning outcomes of the topics and how fully they are reflected. Potential gaps or missing aspects were identified, thus helping to ensure that the content is aligned with the standard and to develop the curriculum and methodological materials in line with the standard.

Based on the results of the teacher survey, it was concluded that the School 2030 Biology I curriculum is not able to provide meaningful learning of biology at an optimal level. The insufficient number of lessons does not allow teachers to carry out laboratory work, include experiments, discussions, and provide individual student support, which is essential in a competence-based approach. The lack of coherence between topics and sub-topics contributes to the fragmentation of biology knowledge and affects students' understanding. In addition, the teaching of topical topics, such as immunity and evolution, lacks resources that comply with the recent developments of science. Teachers often have to adapt or create materials themselves, which increases time consumption and distracts from the individual needs of students. Unclear guidelines on the depth of topics to be covered lead to uneven understanding of the content and differences in interpretation among teachers, which can affect students' prior knowledge, as may already be the case of biology acquisition in primary school.

Teachers' insights were taken into account in the development of the methodological material. To support the biology teacher, an alternative set of methodological materials Biology I has been developed. The developed teaching materials ensure a structured, reflective, and standard-compliant teaching process, with clearly defined learning outcomes, methodological comments, and resources for each lesson. The accompanying supplementary materials, including student worksheets, laboratory work, end-of-topic tests, and other resources, contribute to a multifaceted learning process. All materials are available on the authorised skolo.lv website, providing easy and free access for teachers and students, thus contributing to the digital transformation of education, making it inclusive and open.

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Implications and Recommendations

To enhance the quality of biology learning in a competence-based approach, systemic actions are needed: increasing the number of lessons, logically restructuring the curriculum, providing teaching resources, and developing clear benchmarks. These changes should be based on research-proven methods to ensure that students have the opportunity to learn life sciences as an integrated set of knowledge and skills.

As the mapping of learning outcomes did not show 100% compliance with the educational standard, not only the content but also methodological adjustments need to be made in future. The identified gaps showed that some learning outcomes of the standard are not explicitly reflected in the list of outcomes to be achieved in the programme, and this may create risks that these outcomes will not be achieved in the learning process. During the development of Biology I methodological materials, a mapping of outcomes was carried out, thus ensuring the inclusion of all learning outcomes. In the future, it would be advisable to clearly define and systematically map the learning content in order to avoid fragmentation and ensure the effectiveness of the competence-based approach. In order to harmonise educational standards - at primary, Biology I and Biology II levels - education policy makers, academic staff, and teachers should work together to identify existing coherence and suggest options for further optimisation of the educational content.

In order for the Biology I curriculum in Skola2030 to meet the objectives set out in the education standards, the number of biology lessons should be increased. According to the current Cabinet Regulation No. 416 (Ministru kabinets, 2019) schools can increase the total number of hours by 7-15% for this subject. It would be advisable to 1) review the sequence of topics and sub-topics, following the logical development of concepts (first cell structure, then DNA and heredity); 2) update teaching materials, especially in topics related to contemporary challenges (immunity, biotechnology); 3) clearly define the level of coverage of topics in the standard documents to ensure a uniform approach across schools.

The alternative set of teaching materials for Biology I has addressed the above-mentioned content inconsistencies. The digital platform skolo.lv provides the materials in an open format (PDF, DOC), allowing teachers to customise them. The current focus is on correcting and improving the materials, but in the future, they should be complemented with interactive and digital possibilities such as online tests and simulations. The development of an explanatory glossary of biology terms could be a topical issue. The inclusion of differentiated tasks and interdisciplinary materials could also enrich the learning process and stimulate students' interest in biology, despite the insufficient number of lessons.

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Declaration of Interest

The authors declare no competing interest.

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THE CONCEPT OF FORCE: AN EDUCATIONAL ITINERARY WITH A HISTORICAL SUPPORT

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Abstract

The problem here dealt with concerns physics education, and specifically the concept of force. The idea behind this research is that a historical approach to the teaching of such a notion is of great help for the students to fully understand the meaning of this basic physical magnitude. For, most of scientific concepts can be better grasped by the learners if their genetic phase is presented and the problems that induced scientists to introduce them are expounded. In this way, the students will catch the rationale behind the birth of scientific notions. Furthermore, a shared educational itinerary among the teachers of physics, mathematics, history, and philosophy can be conceived so as to realize an interdisciplinary approach to science education. It is often presented as a desideratum, but is rarely concretely developed. Here, restricting to the notion of force, such an approach is developed. Since force is strictly connected to inertia and mass, a large part of this discussion is dedicated to such two notions.

Keywords. *Newton, physics education, history of science, mass, inertia, force, principles of dynamics, inertial reference frames, non-inertial reference frames*

Introduction

The concept of interdisciplinary instruction is one of the basic notions of modern education. Nevertheless, there are not many cases in which genuine interdisciplinary educational itineraries are proposed. In this research, I will present one: the final purpose is to highlight the main characteristics of the concept of force in physics. Force is strictly connected with mass and inertia, so that it is impossible to deal with the first magnitude without also addressing the nature of the other two. Thence, the protagonists of this writing are mass, inertia, and force.

In many cases, even though not in all cases, the best approach for the students to deeply understand scientific concepts is the historical one. For they will be able to grasp the nature of the concepts in their nascent phase, and this shall allow them to catch all the difficulties that lay behind the birth of some notions, which is sometimes obscure if a more formal approach is proposed. The further advantage of the historical method is that it permits to understand the evolution of science and the relationship between science and the phenomena that science itself attempts to model. Indeed, throughout the history of science, there were considerable difficulties in distinguishing between what belongs to the world and what, on the other hand, belongs to our model of the world. The analysis of these difficulties is a useful tool in the hands of the teacher to help students understand the nature of science.

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Therefore, an interdisciplinary educational approach in which history of science represents a support for science education is here proposed (for the importance of history of physics in physics education see, e.g., Bussotti, 2021, Bussotti, 2023b, Galili, 1993, 2001, Galili &Bar, 1992, Lopes Coelho, 2007, 2010, 2012, 2018, Tomara, Tselfes & Gouscos, 2017. For the relation between mathematics and history of mathematics, see Bussotti (2012, 2013, 2014, 2015b, 2019, 2023a). In what follows, several considerations which also have a philosophical value are presented. A typical example is the just mentioned problem regarding the relations between our scientific models and the reality they describe.

In Italy, force is introduced in the third year of high school, when the learners are between 16 and 17 years old. In the lyceums, history and philosophy are also taught, so that an educational project as the proposed one can be performed. This is, obviously, the case in all schools where physics, history, and philosophy are taught. If, as in many countries happens, philosophy is not taught, the considerations here presented can be developed by a collaboration between the teacher of physics and the one of history.

While speaking of mass and force, there is no doubt the fundamental reference text is the monumental work by Isaac Newton (1642-1727) *Philosophiae naturalis principia mathematica* (*Mathematical principles of natural philosophy*, Newton, 1687, 1713, 1726, resp. first, second and third edition. English translation, Newton 1999). With reference to inertia, Galileo Galilei (1564-1642), René Descartes (1596-1650) and Christiaan Huygens (1629-1695) grasped many aspects of such fundamental as well as elusive concept, but the first scientist who constructed a whole system of physical causality relying on the concept of inertia was Newton. Ergo, in this case too, the paramount reference text will be his masterpiece. It is appropriate to stress that we will restrict to dynamics and to classical physics. Therefore, there will be no references to the notion of force in relativity and in quantum mechanics.

The educational considerations here developed are dedicated to the pupils attending the last three years of the high school, when mechanics is dealt with. In this research, the reader will also find some considerations which are more complex and cannot be proposed to the students. They are dedicated to the teachers for them to contextualize the concept of force in a more profound manner. The main aim of this research is to show the way in which history of science can be used in science education. The method here followed consists in referring to the ideas developed by Newton, the father of modern physics, on the concept of force, to comment them and to see how they can be applied in an educational context.

The Concept of Mass

This notion is a cornerstone of modern physics. Before a specific lesson dedicated to it, almost surely, the students do not separate mass from weight. This is comprehensible: in the course of the history, great scientists did not distinguish between the two notions, and the ideas were confused until Newton gave the first definition of mass. At the beginning of his masterpiece, as the first definition, he wrote:

> *Quantity of matter is a measure of matter that arises from its density and volume jointly.*
> If the density of air is doubled in a space that is also doubled, there is four times as much

https://doi.org/10.33225/BalticSTE/2025.47

> air, and there is six times as much if the space is tripled. The case is the same for snow and powders condensed by compression or liquefaction, and also for all bodies that are condensed in various ways by any causes whatsoever (Newton, 1999, p. 403).

Thus, Newton defines mass as the quantity of matter. Since he was an atomist, mass is given by the quantity of atoms in a given volume. It is appropriate to recall to students that this definition is not satisfactory under one respect: it involves the notion of density, which is not easy and cannot be given for granted. For there is the risk of circularity: to define mass through density and density through mass, which obviously does not work from a logical standpoint.

However, Newton's merit is enormous: he identifies mass as an intrinsic property of each body, which is not the case for weight, which is, instead, equal to mass multiplied by gravity acceleration. It is to point out that here it is not necessary to introduce the concept of force. The notion of acceleration is enough. It is appropriate to anticipate to the students that the origin of gravity acceleration will be clarified after the introduction of the concept of force and that, for the moment, the notion of acceleration is sufficient.

This means that, given a body, its mass is the same everywhere, whereas its weight varies: on the Earth, gravity acceleration has a value; on Jupiter, a bigger value; on the Moon, a smaller value, and in the void space its value is null. The weight varies consequently, whereas the mass does not.

The second definition concerns the quantity of motion as the product or mass by velocity. The third is fundamental and sounds like this:

> *Inherent force of matter is the power of resisting by which every body, as far as it is able, perseveres in its state either of resting or of moving uniformly straight forward.* This force is always proportional to the body and does not differ in any way from the inertia of the mass except in the manner in which it is conceived. Because of the inertia of matter, every body is only with difficulty put out of its state, either of resting or of moving. Consequently, inherent force may also be called by the very significant name of force of inertia. (Newton 1999, p. 404).

Here, there is an anticipation of the inertia principle with which we will deal in the next section. In this context, the aspect to be remarked is that here mass is not associated to weight, but to another property of the bodies: their power to resist to any change of their kinetic state. Let us call the mass associated to weight "gravitational mass" and the mass associated to the inherent force "inertial mass". Inherent force has nothing to do with what we call Newtonian force. For the former is an intrinsic property of bodies, whereas the latter indicates an interaction, as we will see. For the moment, let us focus on a further aspect: a physical quantity makes sense if it is possible to measure it. How do we proceed in the case of mass? Suppose we have a trolley at rest; we impart a push to it by machinery. Suppose the road is perfectly smooth, without any friction. The trolley will start with a certain speed. Now, suppose we have another trolley. We use the same machine to push it, but its speed from 0 becomes three times that of the previous trolley. Based on the definition of inertial force, it is easy to extrapolate that the mass of the second trolley is 1/3 of that of the first one. This is, however, certainly not a very practical way of determining masses and, in fact, one proceeds otherwise. We simply use a balance and divide the result by gravity acceleration.

https://doi.org/10.33225/BalticSTE/2025.47

Nonetheless, we are measuring, at least in principle, two different quantities: for, the first way of measuring mass has nothing to do with Earth's gravity. It works in every region of the universe. While for the second one, gravity is indispensable. If, in fact, the Earth did not attract bodies, it would be impossible to weigh anything. Surprisingly, the two results show that the two masses are equal. This is astonishing because, in fact, they depend on two very different properties. With the trolley experiment we measure the amount of inertia a body has, its resistance to change of motion, which is why we speak of inertial mass. By weighing a body, we measure the degree to which it is attracted by the Earth. That is why we speak of gravitational mass. That the two masses are equal is not a consequence of the theory at all. It is a mere coincidence. From the point of view of classical physics, the identity of the two masses is accidental.

This is an aspect that the teacher has to underline because such a strange and, at the same time, fundamental coincidence must induce to reflect on the fact that a scientific theory cannot explain every aspect of the phenomena. Newtonian physics, which is so efficient to foresee and explain many phenomena, is not suitable to explain the coincidence between inertial and gravitational mass. One might assume that such a coincidence exists independently of any explanation and that it is inscribed in the nature. As a matter of fact, this is the behaviour held until the theory of general relativity, where it is possible to prove that such coincidence is not casual. Connected with this aspect, there is also a methodological-philosophical one: a scientific theory is never a final view on reality. Science is a continuous approximation to reality, which is destined to catch even more inclusive aspects of reality itself, but that can never catch all of them. This is an idea claimed by many scientists, mathematicians, and philosophers. The first who clearly explained it was Federigo Enriques (Enriques 1906). Newtonian physics is a good approximation of reality; relativity theory is a better one that enables us to catch more profound aspects of reality, such as the coincidence between inertial and gravitational mass.

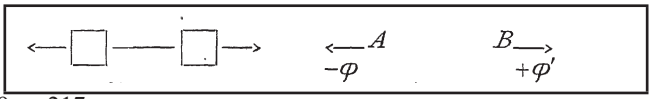
Let us now come back to the definition of quantity of matter given by Newton. We have seen that, although it catches the fundamental difference between mass and weight, it is not completely satisfactory because it relies on the problematic concept of density. To overcome this difficulty, Ernst Mach (1838-1916) gave a relational definition of mass by first defining when two masses are equal. He wrote:

> All those bodies are bodies of equal mass, which, mutually acting on each other, produce in each other equal and opposite accelerations (Mach, 1919, p. 218. See also Barton (1946, Brown (1960, Jammer (1961, Jammer (1999, Roche (2005).

Afterwards, Mach explains as follows: when two bodies have different masses (Figure 1):

Figure 1

The Diagram Used by Mach to Explain His Conception of Mass



Note. Mach 1919, p. 217.

https://doi.org/10.33225/BalticSTE/2025.47

Consider two bodies *A* and *B*, which, because of their mutual interaction, receive respectively the accelerations -φ and +φ' (Figure 1). In this case, by definition, *B* has φ/φ' times the mass of *A*. This definition of mass has an operative value. For, if one assumes that a body *P* has a unitary mass, then a body *P*' has mass *m* if the acceleration it imparts to *P* is *m* times the acceleration *P* imparts to *P*'. This operative definition depends, hence, on the possibility to measure accelerations, but it is deprived of all the problems deriving from the notions of density, and no theoretical notions are necessary if not kinematical elementary ones such as acceleration. Mach stresses this aspect:

> In our concept of mass, no theory is involved; "quantity of matter" is wholly unnecessary in it; all it contains is the exact establishment, designation, and denomination of a fact (Mach, 1919, p. 218).

A problem could arise: is it true that two bodies which, acting with *A* behave as equal masses, also act as equal masses in a reciprocal interaction? Mach underlines that this cannot be given for granted because there is no logical necessity that imposes this to be the case. Through a physical reasoning, Mach is, anyway, able to show that this happens (Mach, 1919, pp. 219-220).

With Mach's definition, the concept of inertial mass receives a more satisfactory characterization, although, obviously, the problem of the coincidence between inertial and gravitational mass remains unsolved.

From an educational point of view, it is appropriate to highlight the kind of definition used by Mach. It is a definition by abstraction: this means that a concept is defined by indicating when two quantities are equal with respect to that concept. Namely, a class of equivalence is enucleated. Of course, it is then necessary to clarify when two quantities are not equal with respect to that concept. This kind of definition is very important in mathematics and, especially, in modern mathematics. Euclid (IV-III century B.C.) defines the concept of proportion by abstraction (Euclid, 2008, Book V, pp. 130-131), Georg Cantor (1845-1918) defines the concept of cardinal number of a set by abstraction (Cantor, 1878), Gottlob Frege (1848-1925) defines the concept of natural number by abstraction (Frege, 1980, original 1884). These are only significant examples of definitions by abstraction. In the prospective of an interdisciplinary education, these aspects which join physics and abstract mathematics must be underlined. Mathematics is not only the unavoidable instrument of physics; the two disciplines also share basic conceptual elements, such as the possible way of defining the concepts.

The Concept of Inertia

The concept of inertia is the milestone of the whole classical physics. It is difficult, not intuitive, and very abstract. In a serious approach to physics, it is necessary that the learners fully grasp the features of such notion. It is appropriate to deal with inertia in two phases: the first one before introducing the concept of force, which I will do in this section, and the second one after having introduced the concept of force. Since the latter shall be presented in the fourth section, the fifth one will be devoted to the definitive re-conceptualization of inertia.

Although Galilei (Galilei, 1967, II, p. 190; Galilei, 1914, IV, p. 244. See also Bussotti & Pisano, 2025, where references to literature are also referred to), Descartes (Descartes, 1984, pp. 240-241. See also Bussotti & Lotti, 2022, pp. 126-132), and

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Huygens (Huygens, 1703, posthumous. See also Bussotti & Lotti, 2022, pp. 162-177, Stan, 2016) expounded propositions similar to inertia principle and the last one also developed a theory of impacts partially based on it, the first complete physical system based on inertia principle was that of Newton. He stated as follows such a principle or law:

> *Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed.* Projectiles persevere in their motions, except insofar as they are retarded by the resistance of the air and are impelled downward by the force of gravity. A spinning hoop, which has parts that by their cohesion continually draw one another back from rectilinear motions, does not cease to rotate, except insofar as it is retarded by the air. And larger bodies–planets and comets–preserve for a longer time both their progressive and their circular motions, which take place in spaces having less resistance (Newton 1999, p. 416).

To explain this principle, a formal definition of force is not necessary, it is sufficient to think intuitively of an action tending to change the kinetic state of a body. A reappraisal of the principle will be done after the introduction of the concept of force.

Therefore: the state of rest is considered dynamically equivalent to that of uniform rectilinear motion. Both would be eternal, if no external action were present.

First conceptual and educational problem: most of the young people aged 16-17 years are influenced by their perceptive experiences, which seem to be in contradiction with the principle. For if an object is moving on a plane and you apply no external action, it perseveres its motion for a more or less long time, but at a certain instant it stops depending on the material of the plane and of the object. Its motion depends on the form of the object too. It is not necessarily uniform and rectilinear. If one looks at the planetary movements, the young will be impressed by the regularities of such movements, which, certainly, are not rectilinear and uniform, although, at all appearances, no action is exerted on the planets. Let us imagine that a student be particularly gifted and that she/he be able to overcome all these difficulties, also relying upon the explanations of the teacher. A crucial difficulty remains. For this student can ask: "Dear teacher, you speak of rest and uniform motion in a right line, but in respect to what do you determine these kinetic states? For me, in my car, I am at rest and the external world is moving; for the external world, I am moving. What is the situation?" (Bussotti, 2021, p. 4).

The first concept to be explained is that of *relativity of motion*: no body is at rest or in motion in an absolute sense. We are free to choose what body is appropriate to consider at rest based on the problem we have to study: generally, for questions connected to local motion, the Earth is considered at rest, although it is not.

There are several sensorial and visual experiences that can indicate the relativity of motion. Everyone has noted that if a train starts slowly, the passengers have the impression that the train remains at rest and that the station is moving.

Let us now move to the concept of inertia. In the experimental physics laboratory, the teacher could develop such an experiment divided into three phases. In the first phase (Figure 2 left side), two joined equal inclined planes are considered. Be the planes are completely smooth. A ball in A is at the altitude h. Under these conditions, the learners will recognise that, after having reached the basis of the two planes in B, the ball will re-ascend in C at the height h. If you like, you can replace the two inclined planes by a circumference.

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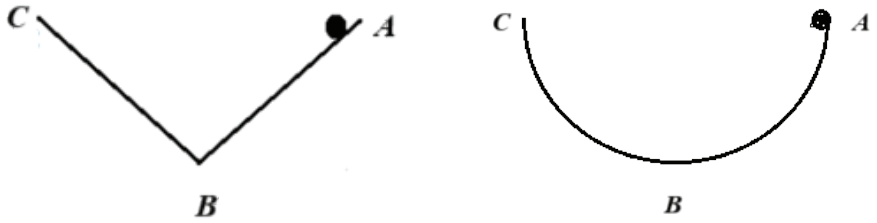
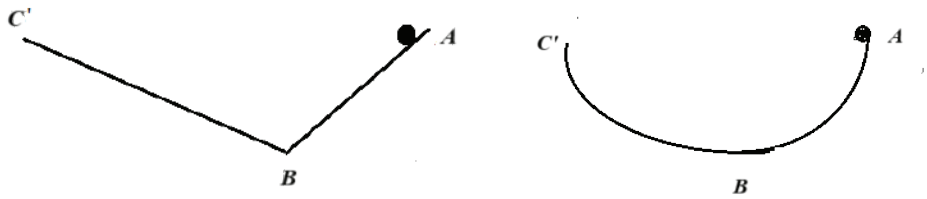
Figure 2
Diagrams Showing the First Part of the Experiment



Note. For the Image on the Left. See Bussotti, 2021, p. 5.

Let us now suppose that the second plane is less inclined on the horizon than *AB*, or, equivalently, that a line having a lesser curvature than the circumference *ABC* is joined in *B* at the quart of circumference *AB* (Figure 3). As before, let the ball start in *A* from the altitude *h*. The students will see that the ball will reach the point *C*', whose height is *h*.

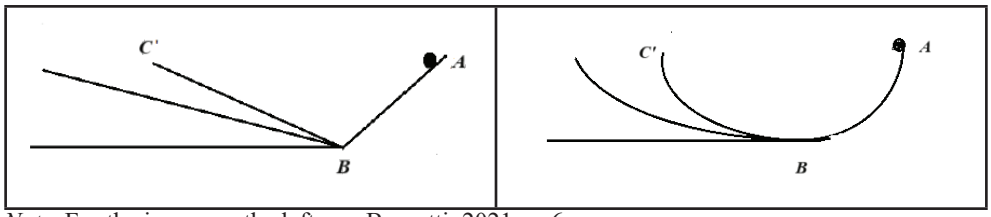
Figure 3
Diagrams Showing the Second Part of the Experiment



Note. For the image on the left, see Bussotti, 2021, p. 5.

Suppose now that the plane *BC*' becomes less and less inclined on the horizon or, equivalently, that the curvature of the line *BC*' continually becomes lesser until being a straight line (Figure 4).

Figure 4
Diagrams Showing the Third Part of the Experiment



Note. For the image on the left, see Bussotti, 2021, p. 6.

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Now the teacher can ask his students: suppose the second plane is horizontal; the ball reaches *B*, what happens afterwards? Probably most learners will correctly answer: the ball arrives at *B* with a certain speed, after that it continues its motion along the horizontal plane with the same speed as in *B*.

This simple experiment can, thus, be useful to convince the students that inertia principle holds. Obviously, this is not a proof, because inertia law is a principle, not a theorem. However, it is an experiment which makes the principle intuitively plausible. It is appropriate to recall that Galileo, in the Second Day of his *Dialogue Concerning the Two Chief World Systems* (1632, Galilei, 1967), developed a reasoning whose synthesis has here been explained. The teacher might read in the classroom this passage of the *Dialogue* (*ibidem*, pp. 145-146). This reading is useful to catch all the difficulties that the most brilliant minds encountered to reach inertia law. Thus, the human aspect of science will be highlighted: the scientists reached the notions which are the bases of our knowledge of the external world through a road full of obstacles. Only their hard work permitted to overcome the obstacles (Bussotti, 2021, p. 6).

Some didactical considerations are appropriate: the argumentation here expounded depends on the assumption that the two inclined planes have perfectly smooth surfaces, so that no friction exists. However, this condition is impossible. A surface can have a negligible friction, but not a null friction. What is the consequence of this observation? Is the inertia principle unacceptable from a physical standpoint? The teacher has here an important task: she/he must explain the difference between the universe and our model of the universe to her/his pupils. Inertia principle is an element of our world model, which shows a tendency of the real bodies. It is unavoidable to grasp their kinetic behaviour. In the real universe, no motion is perfectly inertial. The model must provide us with a conceptual scheme such that, if we abstract from some properties *P* (in this case that no surface completely deprived of friction or no body on which no action is exerted can exist), then we can focus on properties *Q*, like inertia, that, although not rigorously existing, can help us to understand profound aspects of the universe. Each situation physics examines deals with our theoretical model, which is a simplified view of reality. Our model is the more satisfactory the more elements of reality it can explain and foresee, but every model will abstract from some aspects of reality, and, hence, it is, for some aspects, incomplete.

A crucial consideration concerns the uniformity and rectilinearity of a motion: we have underlined that every motion is relative. On the other hand, inertia principle seems to speak of uniform rectilinear motion as an absolute kinetic state. How can these two conditions be conciliated? From an operational perspective, this problem can easily be solved. For every problem we address, there is a set of motions which can be regarded as rectilinear and uniform. Let us suppose we want to study the movement of a vehicle on a road without curves and located at a uniform altitude above sea level. If this motion is not accelerated in modulus, it can be regarded as rectilinear and uniform, although it is not because the Earth is not flat, because it is rotating around its axis and around the Sun, and so on. However, if we are interested in the motion of our vehicle, it can be considered rectilinear and uniform when its velocity is subject to no variation in modulus. Therefore, from an operational point of view, there is no problem. Nonetheless, there are many problems from a foundational point of view, namely, if we claim that inertia is an absolute and not an operative concept. We will outline this difficult issue after having introduced the concepts of force and of inertial system.

https://doi.org/10.33225/BalticSTE/2025.47

Finally, a brief observation: according to inertia principle, uniform rectilinear motion continues without the need of any external action. Therefore, this means that such an action does not cause velocities, but changes of velocities, namely accelerations. This action is what Newton called *force*.

The Concept of Force

Since not all motions are rectilinear and uniform, an action is necessary. Let us call such an action force. From an educational perspective, one can choose to simply define force $\boldsymbol{F}$ as the product of mass m by acceleration $\boldsymbol{a}$, so reaching the well known formula $\boldsymbol{F}=m\boldsymbol{a}$. This approach is not wrong but hides several interesting aspects of the concept of force, which can, instead, be highlighted by following Newton's order of ideas, which is what we will do here.

Newton's first Definition concerning force as action is the fourth one of the *Principia*:

> Impressed force is the action exerted on a body to change its state, either of resting or of moving uniformly straight forward (Newton, 1999, p. 405).

As the most significant examples of impressed forces, Newton speaks of impact, pressure, and centripetal force. Impact and pressure act by direct contact between bodies, but what about centripetal force? Newton clarifies his nature in the following fifth Definition:

> Centripetal force is the force by which bodies are drawn from all sides, are impelled, or in any way tend, toward some point as to a centre (*ibid*., p. 405).

The first and fundamental centripetal force mentioned by Newton is gravity.

Here, several educational as well as conceptual observations are necessary:

1) Gravity has a different character with respect to impact and pressure. For, the latter act directly by contact, whereas gravity does not. When a body descends towards the Earth's surface, there is no contact between the body and the surface. The planets, as Newton will prove, gravitate towards the Sun, but there is no direct contact between the planets and the Sun. This means that gravity acts at a distance. In the course of the history of physics there were, before and after Newton, various attempts to find an ethereal medium which could transmit gravity (see, e.g., Bussotti & Lotti, 2022, chapters 5, 6, 8) and Newton himself was not convinced of the action at a distance, as a famous letter to Richard Bentley (1662-1742) on 25 February 1693 clarifies (Newton, 1756, posthumous). However, no satisfying intermediary medium was found, so that gravity in Newtonian physics is, in fact, an action at a distance. Here, an observation is appropriate which connects the teaching of physics with that of history and of philosophy: Descartes (see Descartes 1984, first edition 1644) had tried to propose a series of mechanisms which explained all the actions simply by impacts and motions. His attempt was reasonable: in the Medieval period and, above all, in the Renaissance, astrology and natural magic was developed (see, e.g., Dawes, 2013, Frank, 2009, Hanegraaff, 2012, Humphreys & Wagner, 2013, Kristeller, 1964, Mebane, 1989, Thorndike, 1923). Such

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disciplines claimed to explain many effects which take place on the Earth as due to mysterious influxes of asters and celestial bodies which act at a distance. Descartes and other scientists of the 17th century refused such a conception. Thence, Descartes tried to develop a system where, by supposing the existence of a particular matter he called ether, all the interactions could be explained by direct contact. Descartes did not develop the mathematical part of his system, but, especially Huygens, and in part Leibniz did (Bussotti, 2015a). Therefore, in the perspective of Huygens and Leibniz, Newton's action at a distance was criticised because it seemed to reintroduce mysterious entities which physics had tried to rebel against. Leibniz, particularly, developed a series of argumentations against the action at a distance (see, e.g. Bouquiaux, 2008, Bussotti, 2015a, Cox, 2002, Duchesneau, 2004, Gale, 1988, Garber, 2009, Leibniz, 1690, Leibniz, 1977, Look, 2011, Miller, 1982, Ramati, 1996, Roberts, 2003). However, it is to point out that the physics based on the existence of an ethereal medium did not achieve any results that were remotely comparable to those obtained by Newton. This teaches us that science is not a theory of everything: the origin of gravity was unknown, but Newton was perfectly able to explain its effects and, at least, in a certain phase of science, this is absolutely acceptable. It makes no sense to refuse an almost perfectly working theory because the origin of the concept of force that is at its basis is unknown. Of course, this does not mean that research on such origin must be neglected. The picture here presented is useful for the students to understand many nuances of what a scientific theory is and how it is developed.

2) We have spoken of forces acting at a distance and by contact. It is appropriate to add that, when the studies on electricity and magnetism were developed, in great parts thanks to the works of physicists and mathematicians such as Charles Augustin de Coulomb (1736-1806), Luigi Galvani (1737-1798), Alessandro Volta (1745-1827), Carl Friedrich Gauss (1777-1855), Hans Christian Ørsted (1777-1851), Siméon-Denis Poisson (1781-1840), Michael Faraday (1791-1867), James Clerk Maxwell (1831-1879), Faraday had the enormous merit to introduce the concept of magnetic field in physics. This entity was exactly the one that mediates magnetic force. Therefore, magnetism, and after Maxwell, electromagnetism, studies a force which acts by contact through the intermediary of a field. But, in classical physics, although the notion of gravitational field is used, no intermediary comparable to magnetic, or electromagnetic field, has ever been found. It is to add that partially connected to the history of magnetic and electromagnetic fields, there is also that concerning light transmission. Here things are really complicated because, along the whole 19th century, there was a huge discussion on the mysterious intermediary medium (also called ether) which should have transmitted light (Whittaker, 1910).

3) Newton explains masterfully how a curved motion takes place: suppose a body has a certain inertial motion. It arrives close to another body, which is a source of centripetal force. Its motion is deviated and becomes curved. So that a curved motion is due to an initial motion and to the action of a centripetal force. Let us refer to his clear explanation, which is well conceived also from an educational standpoint:

> A stone whirled in a sling endeavors to leave the hand that is whirling it, and by its endeavor it stretches the sling, doing so the more strongly the more swiftly it revolves; and as soon as it is released, it flies away. The force opposed to that endeavor, that is, the

https://doi.org/10.33225/BalticSTE/2025.47

> force by which the sling continually draws the stone back toward the hand and keeps it in an orbit, I call centripetal, since it is directed toward the hand as toward the center of an orbit. And the same applies to all bodies that are made to move in orbits. They all endeavor to recede from the centers of their orbits, and unless some force opposed to that endeavor is present, restraining them and keeping them in orbits and hence called by me centripetal, they will go off in straight lines with uniform motion. If a projectile were deprived of the force of gravity, it would not be deflected toward the earth but would go off in a straight line into the heavens and do so with uniform motion, provided that the resistance of the air were removed. The projectile, by its gravity, is drawn back from a rectilinear course and continually deflected toward the earth, and this is so to a greater or lesser degree in proportion to its gravity and its velocity of motion. The less its gravity in proportion to its quantity of matter, or the greater the velocity with which it is projected, the less it will deviate from a rectilinear course and the farther it will go (Newton, 1999, pp. 405-406).

After having defined centripetal force, Newton defines its absolute quantity as the intensity of such a force and its accelerative quantity as a magnitude proportional to the acceleration that such a force produces. In an educational context, it is simply appropriate to speak of acceleration.

The last definition, the eighth one, is important because, as a matter of fact, Newton offers the definition $\boldsymbol{F}=m\boldsymbol{a}$:

> The motive quantity of centripetal force is the measure of this force that is proportional to the motion which it generates in a given time (ibidem, p. 407).

There is no doubt that, in this context, Newton meant by motion, the quantity of motion $\boldsymbol{p}$ he had already defined as $\boldsymbol{p}=m\boldsymbol{v}$. He explains the situation as follows:

> Therefore, accelerative force is to motive force as velocity to motion. For quantity of motion arises from velocity and quantity of matter jointly, and motive force from accelerative force and quantity of matter jointly (ibidem, p. 408).

Since the accelerative force is acceleration $\boldsymbol{a}$, the quantity of motion is $m\boldsymbol{v}$, if we indicate the motive force by $\boldsymbol{F}_{\mathrm{m}}$, the proportion follows

$$\boldsymbol{a}:\boldsymbol{F}_{\mathrm{m}}=\boldsymbol{v}:m\boldsymbol{v}.$$

Therefore, $\boldsymbol{F}_{\mathrm{m}}=m\boldsymbol{a}$. Newton was restricted to considering centripetal forces because he was particularly interested in gravity. Nonetheless, there is no problem to offer such a definition as that general for a force. However, after the whole educational itinerary here presented, this definition has a full justification, the conceptual and historical reasons for its introduction are clear, and this concept does not appear as something imposed without any justification. A brief observation can be added: Newtonian historiography has lengthy dealt with the question whether Newton regarded a continuous force, like gravity, as the sum of an infinite series of infinitesimal impulses (see, e.g. Bernard Cohen, 1967, Blay, 2001, Ellis, 1965, Ellis 1976, Erlichson, 1991, Jammer, 1962, Pourciau, 2006, Westfall, 1971). There is no doubt that, in some circumstances, for example in Proposition I, where he proved the area law, this is the case. However, Newton's procedure is related to his mathematical technique rather than to his physical conception of force, and I support

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the idea that he did not consider a continuous force as generated by impulses. Since this topic is not directly connected to our educational context, it is not addressed to it. The reader can form his own opinion by resorting to Newton's text and to the mentioned literature.

We are now ready to introduce the second law of motion, which sounds:

> A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed (Newton 1999, p. 416).

Let us now develop some observations:

1) The first one concerns the concept of "change of motion". There are many interpretations on what Newton meant by this expression (the previous reference to literature also applies in this case). This is a fundamental issue for Newtonian historiography. However, considering that in the eighth Definition Newton identified motion with quantity of motion, it seems reasonable to assume that "change of motion" means "change in quantity of motion" (see, e.g., Jammer, 1962, pp. 124-126), that is $\boldsymbol{F} = \frac{d(m\boldsymbol{v})}{dt} = m\frac{d\boldsymbol{v}}{dt} = m\boldsymbol{a}$. This choice is also the easiest from an educational point of view.

2) The second observation regards a crucial aspect: one might get the idea that Newton's second law is a definition of force. But, in fact, it is not. Newton had already defined force, as we have seen, and forces can be measured independently of dynamics. For example, the force exerted by a spring is experimentally found to be proportional to the spring compression or elongation, according to Hooke's law. Therefore, there is no reason to offer a further statement equivalent to a definition. For, the second law establishes an equation between a quantity whose expression is fixed and a quantity whose expression is variable from problem to problem. The former is $m\boldsymbol{a}$, or, as it is usual to write in dynamics $m\ddot{\boldsymbol{x}}$, where the overwritten dot indicates derivative (in this case of position x) with respect to time, and two dots the second derivative with respect to time. The aim is to find the expression of position in a function of time, the so-called equation of motion.

An example which is not so trivial as to be obvious, nor so difficult as to be problematic for the students, is that of a simple pendulum (Figure 5. The treatment is drawn from Sonego 2023, pp. 81-82).

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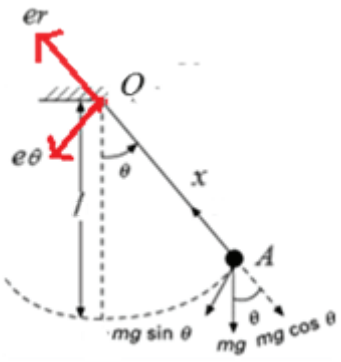
Figure 5
Diagram Describing the Movement of a Simple Pendulum



Suppose no friction exists. Thence, the particle A is subject to its weight $m\boldsymbol{g}$ and to the constraint force $\boldsymbol{\phi}$, which is perpendicular to the circumference on which A moves. Let us introduce an orthonormal basis $(\boldsymbol{e}_r,\boldsymbol{e}_\theta)$, with parallel to $\boldsymbol{x}$, so that $\boldsymbol{x} = \boldsymbol{OP} = l\boldsymbol{e}_r$ and $\boldsymbol{\phi} = \phi\boldsymbol{e}_r$. Therefore, Newton's second law supplies the equation

$$m\ddot{\boldsymbol{x}} = m\boldsymbol{g} + \boldsymbol{\phi} \qquad 1).$$

As we have told, $m\ddot{\boldsymbol{x}}$ is the general fix expression which indicates all the forces acting on a system and $m\boldsymbol{g} + \boldsymbol{\phi}$ indicates the specific forces acting in the problem of the simple pendulum. Looking at the figure, it follows immediately

$$m\ddot{\boldsymbol{x}} \cdot \boldsymbol{e}_\theta = m\boldsymbol{g} \cdot \boldsymbol{e}_\theta = -mg\sin\theta \qquad 2),$$

where the dot indicates scalar product and θ is the angle that $\boldsymbol{OP}$ forms with the downwards direction through O, measured positively in the counterclockwise direction. The velocity of A is $\dot{\boldsymbol{x}} = l\dot{\boldsymbol{e}}_r$. Since, it is easy to prove that $\dot{\boldsymbol{e}}_r = \dot{\theta}\,\boldsymbol{e}_\theta$, it follows that $\dot{\boldsymbol{x}} = \dot{\theta}\,\boldsymbol{e}_\theta$. By differentiating with respect to time, we find the acceleration:

$$\ddot{\boldsymbol{x}} = -l\dot{\theta}^2\boldsymbol{e}_r + l\ddot{\theta}\boldsymbol{e}_\theta.$$

Replacing this value in Equation 2, one finds the differential equation for the function $\theta(t)$:

$$\ddot{\theta} + g/l\sin\theta = 0.$$

If equation 1) is multiplied scalarly by $\boldsymbol{e}_r$ the following equation for the constrain-force is obtained:

$$\phi = -ml\dot{\theta}^2 - mg\cos\theta.$$

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Our problem has now to be reduced to the solution of two differential equations, which, in this case, can be solved analytically, so as to offer all the physical quantities required. Of course, in most cases, the equations cannot be solved analytically, but the form and the purposes of Newton's second law are clear: offering the equations of motion.

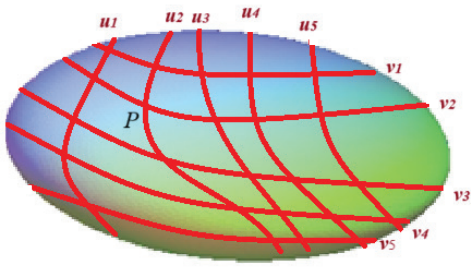
3) In Corollary I to his laws of motions (Newton 1999, pp. 417-418) Newton established the rule for the sum of two vectors (parallelogram rule) as well as the property that the effect of a force on a body does not depend on the body's state of rest or motion or on the presence of other forces simultaneously acting on the body.

4) The following one is an observation of utmost importance from the conceptual and educational standpoint: several scholars, among whom Mach (Mach, 1919, p. 242), claim that the first law is included in the second one or, even, in the definition of force. This is false, and Newton was completely correct to separate the definition of force, the first and second laws. This involves a profound relation: that between inertial and non-inertial reference-frames, which is the topic we will address in the next section.

Inertial and Non-Inertial Reference Frames

It is impossible to develop physics without the notion of a reference frame. This is connected to four aspects: 1) identification of the position of an object, 2) metric questions, 3) kinematical and 4) dynamical issues: with regard to the first two aspects, a system of coordinates is sufficient. As to the position of a point, it is not necessary to have introduced a metric; systems of lines are sufficient. If, for example, we want to identify a point on a bidimensional surface (e.g. an ellipsoid) we can draw two systems of lines u_i and v_i which are subject to only three conditions: 1) each line of both systems does not intersect itself; 2) each line of both systems does not intersect any line of the same system; 3) each line u_i of the system u intersects all the lines v_i of the system v and vice versa (Figure 6). This is sufficient to identify the position of every point on the ellipsoid without any reference to the concept of distance. For example, the point P will have coordinates (u_2, v_2).

Figure 6
A System of Gaussian Coordinates on an Ellipsoid



The merit of having introduced the general concept of this system of coordinates is by Gauss (Gauss, 2005), even though the parallel and meridians are Gaussian coordinates

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and, of course, were used before Gauss. Gaussian coordinates are fundamental in general relativity and can be introduced by the teacher without any particular problem, provided it be clarified that metric is not necessary to identify a point.

If, besides identifying a point, we want also to calculate distances, a metric structure must be introduced in our system of coordinates. At the high school level, it is sufficient to introduce the Euclidean metric for Cartesian and polar/spherical coordinates. This can be done by adding an origin to our system of coordinates and defining, in Cartesian coordinates, the distance of a point $P(x,y)$ from the origin $O(0,0)$ as $\sqrt{(x^2+y^2}$), if one is working in two dimensions, and of a point $Q(x,y,z)$ from the origin $O(0,0,0)$ as $\sqrt{(x^2+y^2+z^2}$, if one is working in space. The distance between two any points of coordinates (x_1,y_1,z_1) and (x_2,y_2,z_2) will, thence, be $\sqrt{(x_1-x_2)^2 + (y_1 - y_2)^2 + (z_1-z_2)^2}$. The distance in polar and spherical coordinates presents no particular problem and can be found in every handbook of mathematics for high schools.

Until now, we have spoken of geometry and systems of coordinates, but we need to make physics. Therefore, we have to introduce the concept of a reference frame. In physics, a reference system is a system of coordinates relative to which a certain physical phenomenon or object is observed and measured, or certain measurements are taken. This notion is necessary in kinematics and dynamics for the description of the motion of bodies and the observation that motion is always relative to a system with respect to which we observe it. This means that, while a system of coordinates in geometry is a static object (this does not mean that geometrical objects are always regarded as static, for the notion of geometrical motion exists), a reference frame can have every kind of motion with respect to another reference frame.

Let us now come to one of the most fundamental concepts of the whole physics: that of the inertial reference frame. An inertial reference frame is characterised by the condition that, if a material point is free, i.e., subjected to a zero resultant of forces, then it will persist in its state of rest or uniform rectilinear motion as long as it is not disturbed. In other words, an observer or reference frame S is said to be inertial if, given an isolated material point of mass P, the acceleration of P in S is equal to zero, whatever the instant t at which this measurement is made and whatever the kinematic state (P, $\dot{P}$) of the point at the same instant t be.

It can be verified that the observers, who measure the acceleration of an isolated point to be null, are all and only those moving with uniform rectilinear translatory motion with respect to the observer S.

This means that an inertial reference frame is one in which the first law of dynamics holds. Therefore, to change the kinetic state of a body in an inertial reference frame, a force is necessary. This is the reason why the second law depends, in fact, on the first law. Namely, $\boldsymbol{F}=m\boldsymbol{a}$ only in inertial reference frames. An example will clarify what is claimed (Figure 7).

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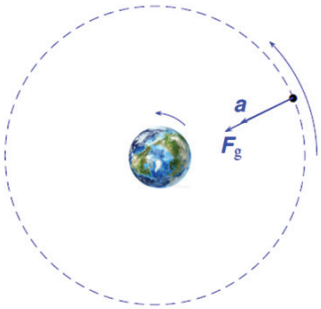
Figure 7

The Movement of a Geostatic Satellite



Let us consider a geostatic satellite. Let us set the origin of our reference frame in the Earth's centre and suppose that the frame does not participate in the diurnal motion of the Earth. Be *M* the mass of the Earth, *m* the mass of the satellite, $F_g = G\frac{mM}{r^2}$ gravity force, where *G* is the Newton constant and *r* represents the distance from the Earth's centre at which the satellite must be set for it to be geostatic, $a = \omega^2 r$ be the satellite's centripetal acceleration, fulfilling the condition $\omega = \frac{2\pi}{T}$, with *T*= 1 day. Gravity force and centripetal force to which the satellite is subject have the same value. Thence, the equation

$$ma = m\omega^2 r = G\frac{mM}{r^2}$$

holds, so that $r = \sqrt[3]{\frac{MG}{\omega^2}}$.

However, no one prevents us from considering a non-inertial reference frame corotating with Earth. In this case, gravity force remains the same, namely $F_g = G\frac{mM}{r^2}$, but in this case, the satellite has no centripetal acceleration *a'* because it is at rest with respect to the centre of the reference frame. This means that *a' = 0*, and, certainly, force is different from ***ma'***.

Therefore, the first Newton's law is necessary, and it establishes the frames for which ***F=ma***, namely the frames in which Newton's second law can be applied. This is a crucial aspect the students must fully understand.

In non-inertial reference frames, other force terms can appear (centrifugal, Coriolis, and Euler forces), but this important development goes beyond the aims of this paper.

Let us now move to another observation which is significant in an educational perspective: reference frames, be they inertial or non-inertial, belong to our model of the physical universe, to our theory. In the world, there is no reference frame. There are events and objects, but not reference frames. The latter are our constructions necessary to develop science. From a historical perspective, the concept of inertial reference frame was formally introduced in 1885 by the German physicist Ludwig Lange (1863-1936) (Barbour & Pfister, 1995, Lange, 1885a, Lange, 1885b, Bussotti & Lotti, 2022, pp. 225-227), but, obviously, concepts analogous to that of inertial frame were already used by

https://doi.org/10.33225/BalticSTE/2025.47

Newton, and even by Galileo. The difference is that Lange clearly distinguished what belongs to our model of the theory from what belongs to the universe. Before Lange, the equivalent of an inertial reference frame was an object or a portion of the physical space sufficiently far from external actions as to be regarded as subject only to an inertial motion. Of course, in the physical world, no object or no portion of space is completely force-free, but there are objects or portion of space which, in relation to the problem one is going to study, can be regarded as subject only to an inertial motion without any detectable error. Thence, the notion of inertial reference frame is precise and belongs to the theory; in the universe, one finds portion of space which can approximately be considered as inertial. The most famous and paradigmatic example is "il gran navilio" ("the big ship") of Galileo: he imagined a ship moving uniformly and rectilinearly with respect to the seashore in a calm sea. If one jumps on this ship, he will land in the same place of the ship, if one looks at a fish tank full of little fishes, he will note that the surface of the tank's water is flat, and that the movements of the fishes is indistinguishable from those they have in a tank on the mainland, if some drops of water fall into a bucket, they will fall as if the ship were at rest. Therefore, only relying upon these observations and experiments, it will be impossible to distinguish if the ship or the seashore is moving (Galilei, 1967, Day 2, pp. 186-188). This means that the ship is the physical equivalent of an inertial reference frame. It is to point out that this is true only very approximately, also neglecting water's friction, because the sea is not a plane, but a portion of an ellipsoidal surface and because the Earth is subject to many motions. However, for the local movement in which Galileo was interested, Galileo's ship can be reasonably regarded as equivalent to an inertial frame.

Newton, in the fifth corollary to his laws of motion, clearly established what happens when a portion of space is at rest or moves uniformly:

> When bodies are enclosed in a given space, their motions in relation to one another are the same whether the space is at rest or whether it is moving uniformly straight forward without circular motion (Newton, 1999, p. 423).

Newton's space is the equivalent of our inertial reference frames. However, it is both part of the theory and of the universe. In Newton's time, the distinction between a model of the universe and the universe itself was not as clear as it is nowadays. This granted, Newton wondered whether in the universe something which were completely at rest and to which all the other inertial movements could be referred could exist. This is an extremely problematic issue, because Newton was well aware, as the previous corollary and the whole of his treatment shows, that two inertial frames (or portion of space) are indistinguishable as to the physical effects. However, though he being perhaps the greatest genius ever existed, he was a man of the 17th century and he felt the need to anchor his inertial spaces and objects to an absolute inertial object, which he thought to have identified in absolute space, an infinite extended container in which the scene of the universe takes place and that exists independently of events and objects.

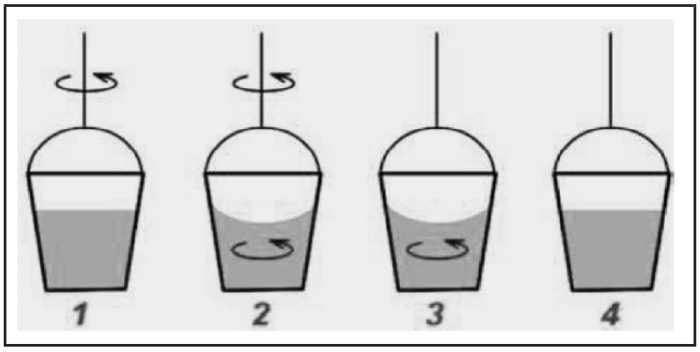
The problem dealt with by Newton is crucial from an educational standpoint, as well. To what can the inertia of a body be referred? In other words, with respect to what can it be determined? Descartes referred every movement of the bodies to that of the neighbouring bodies (Descartes 1984). In the celebrate bucket experiment, Newton proved that the inertia of a body cannot be referred to the neighbouring bodies, but he

https://doi.org/10.33225/BalticSTE/2025.47

went far beyond, thinking to have deduced the existence of an at rest, infinite, absolute space. Let us see his reasoning (Bussotti 2021):

> Consider a bucket hanging at a rope (Figure 8). Act like this:
> (1) Twist the rope until it is very hard and keep the rope twisted;
> (2) Fill the bucket of water;
> (3) Free the rope. You observe that the bucket begins to rotate, but you will observe no movement in the water (picture 1, Figure 8);
> (4) After a little bit of time, the bucket, because of the friction between the particles of the water and those of the bucket's walls, communicates the movement to the water, which begins to rotate and to ascend along the bucket's walls (picture 2, Figure 8);
> (5) After a while, the bucket stops its movement, but the water continues to rotate (picture 3, Figure 8);
> (6) Finally, both the bucket and the water are at rest (picture 4, Figure 8).

Figure 8
Images Showing Newton's Bucket Experiment



Newton interpreted the rotational movement of the water as due to its inertia. He was perfectly right: during its movement, each particle of water tends to escape along its instantaneous tangent because of the inertia principle. Inertia tendency cannot be actualised because of the bucket's walls. Thence, the particles ascend on the bucket's walls, and the entire water's surface assumes a concave form.

Newton wondered to what the ascending movement of the water, namely its inertia, can be referred. The answer is in the following Table 1.

https://doi.org/10.33225/BalticSTE/2025.47

Table 1.
A Summary of Newton's Bucket Experiment

	Relative motion water/bucket	Water's surface	Inertial forces
1.	Max.	Flat	No
2.	No	Curved	Yes
3.	Max.	Curved	Yes
4.	No	Flat	No

The inertia of water cannot be referred to the bucket, because there are effects of the inertial tendency (the ascent of the water and its curved shape) both in the case in which the relative motion water/bucket is null (phase 2) and in that in which it is maximal (phase 3). You note the lack of inertial tendency both in the case in which the relative motion of water/bucket is maximal (phase 1) and in that in which no relative motion exists (phase 4).

Ergo, Newton concluded that water's inertia cannot depend either on the bucket or, even less, on other objects close to the water. He referred inertia to the absolute space he had previously defined, an infinite and neutral container of the whole universe. In this way, the concept of inertia is, in Newton's view, well founded; it is possible, at least in principle, if not in practice, to distinguish the inertial reference frames from the others: they are the frames which are at rest or move rectilinearly and uniformly in respect to the Absolute Space.

Newton was legitimate to conclude that inertia cannot be referred to neighbouring bodies, but he was not to claim it can be referred to absolute space, because such a space can in no way be distinguished from other inertial spaces, or reference frames in our perspective (Belkind, 2007, Bussotti & Lotti, 2022, pp. 207-235, DiSalle, 1994, DiSalle, 2002, Gould, 1962, Hugett, 2008, Reichenbach, 1957, Rynasiewicz, 1995, Stein, 1967). This notwithstanding, Newton's absolute space was accepted by most physicists until the end of the 19th century, with some remarkable exceptions such as Leibniz, because it offered a sort of psychological sureness that the concept of inertial motion, which is so difficulty to be well defined, but at the same time so crucial, is, after all, based on an existing entity: absolute space. With Mach's work, the situation changed because he had the idea to refer the inertia of a body *B* to the presence of all the other bodies of the universe, so that in a universe with different bodies, the inertia of *B* would have been different. It is interesting to remark that, at the beginning of the 20th century, experiments and observations were conceived to prove if Mach's conception was correct, but no detectable result was obtained (see Bussotti-Lotti, 2022, pp. 225-235). The picture dramatically changed with Einstein's general relativity, although, even nowadays, inertia is not easily explainable. But this is another story which goes far beyond the limit of this research. With this panorama on inertia, we hope to have highlighted important aspects useful from an educational perspective.

https://doi.org/10.33225/BalticSTE/2025.47

Brief considerations on Newton's third law

With regard to the third law of dynamics, namely the action and reaction principle, we restrict ourselves to quoting its enunciation and an explanation given by Newton himself, which offers a clear justification of such a principle. We read:

> To any action, there is always an opposite and equal reaction; in other words, the actions of two bodies upon each other are always equal and always opposite in direction. (Newton, 1999, p. 417).

To explain the nature of this principle, Newton developed the following acute reasoning, which is useful in an educational perspective too (ibidem, pp. 417-430): consider two bodies *A* and *B* which mutually attract. Pose an obstacle between the two bodies. If the third law were not valid and one of the two bodies, for example, *A,* were attracted by *B* more than *B* by *A*, the obstacle could not remain in equilibrium because it is more pressed by *A* than by *B*. The system of two bodies-obstacle will, thence, accelerate from *A* toward *B*. But this contradicts the principle of inertia because a system on which no external action is exerted would move with an accelerated motion. This is a perfect explanation of the reason why the third law is necessary in Newton's physics. It depends on the first law, which, ergo, once again shows its crucial aspect in classical dynamics.

Conclusions and Implications

The main purpose of this research is the attempt to underline the role that history of science and mathematics can play within science and mathematics education. I have been working on this project for more than ten years. Basically, I deal with mathematics education (see Introduction), but I also tried to show the usefulness of using the history of physics in the teaching of this discipline with respect to the concept of inertia and energy (see Introduction). The advantage of the historical approach is that the learners can grasp how some concepts were introduced because of the internal necessities of mathematics and physics. These concepts are, thence, comprehended in their genetic phase and become more understandable for the students who can appreciate the work of genial scholars starting from their problems and their conceptions. On the other hand, I do not consider the historical approach to science education a universal access key. For example, in the teaching of quantum mechanics, it is not appropriate to begin relying upon history because Planck reached the idea of energy quantum by studying the black-body radiation, which is a difficult subject, connected to many nuances and problems of physics at the end of the 19th century. There are more suitable ways to introduce quantum mechanics to learners without dealing with the questions connected to black-body radiation. Therefore, I am not proposing a solution valid once and forever. Nonetheless, the historical approach works well on many occasions. Furthermore, it has the remarkable advantage of realizing an interdisciplinary education, which is one of the main tenets of modern pedagogy. It is important that the teachers know different methods to teach their discipline and that they choose the best, also considering the students who are in front of them. The methods can vary according to the quality and the interests of the pupils.

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INTEGRATING MULTIMODAL TEACHING STRATEGIES INTO STEM EDUCATION: REFLECTIONS FROM PRE-SERVICE AND IN-SERVICE TEACHER WORKSHOP EXPERIENCES

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Abstract

The growing emphasis on STEM education and the diverse needs of learners necessitate the adoption of innovative, inclusive teaching strategies. This study investigates the impact of multimodal teaching strategies–integrating visual, kinesthetic, and auditory modes—on in-service and pre-service teachers. Training sessions were conducted with 34 in-service teachers in India and 56 pre-service teachers in Malaysia. The sessions aimed to promote learner-centered practices, enhance instructional confidence, and support inclusive STEM pedagogy. Data were gathered using feedback forms, session presentations, and semi-structured interviews. Content analysis revealed that both groups experienced increased engagement, a deeper understanding of STEM concepts, and a positive shift in attitudes toward creative and collaborative teaching. Strategies such as role-play and play dough modeling were particularly well-received, enabling the transition from teacher-centered to student-centered instruction. These findings highlight the potential of multimodal approaches to enrich teacher education and professional development programs, fostering creativity, inclusivity, and effective communication in 21st-century classrooms.
Keywords: *multimodal teaching strategies, in-service teachers, pre-service teachers, STEM education, teacher training, hands-on learning*

Introduction

Effective professional development for both pre-service and in-service teachers is a cornerstone of contemporary efforts to enhance STEM education. Globally, policymakers recognize that the quality of schooling is closely linked to the capabilities of teachers and administrators within the system. Professional development programs focused on STEM education are systematic initiatives aimed at transforming teachers' classroom practices, reshaping their attitudes and beliefs, and ultimately improving student learning outcomes (Joseph & Uzondu, 2024). Central to this effort is the recognition of multimodal teaching–a pedagogical approach that integrates diverse modes of communication and learning, including visual, auditory, and kinesthetic strategies–to

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engage students in multiple ways (NRC, 2013; NEP 2020). As Mayes and Rittschof (2021) observe, STEM education increasingly promotes interdisciplinary methods that enhance learning experiences.

STEM Education

STEM education emphasizes the integrated teaching of Science, Technology, Engineering, and Mathematics to cultivate critical thinking, problem-solving, and collaboration skills among learners. This interdisciplinary approach prepares students to tackle real-world challenges through practical, hands-on experiences (Sheth & Pathak, 2023). By encouraging creativity and teamwork, STEM fosters competencies essential for innovation and leadership in today's technology-driven world (Yuliardi & Dahlan, 2023).

Learning Styles

Learning styles refer to the varied ways individuals perceive, process, and retain information. Emerging from psychological research in the 1960s and 1970s (Curry, 1987), these styles are explained through models highlighting cognitive preferences. Commonly identified styles include visual, auditory, kinesthetic, and reading/writing modalities, each influencing learners' engagement with content. The theory posits that aligning teaching with students' preferred modalities enhances learning effectiveness (Pashler et al., 2008). This "matching hypothesis" suggests improved educational outcomes when instruction corresponds to learner preferences (Rogowsky, Calhoun, & Tallal, 2020). Oliveira et al. (2023) further emphasize the necessity of adapting instructional materials to diverse learning needs. The Visual, Auditory, and Kinesthetic (VAK) framework remains widely used for categorizing sensory-based learner types (Rose & Nicholl, 2009).

Multimodal Teaching and Learning

In response to rapidly changing educational demands, innovative pedagogical approaches like multimodal teaching have gained prominence. Dual Coding Theory (Paivio, 1986) posits that learning is enhanced when information is presented through both verbal and visual channels. Mayer and Rittschof (2021) support this, demonstrating the positive impact of visual aids on students' understanding of abstract mathematical concepts. The Universal Design for Learning (UDL) framework (Rose & Meyer, 2002) advocates for multiple means of representation to address learner diversity. Cognitive Load Theory (Sweller, 1988) also underscores the role of multimodal design in managing cognitive effort by leveraging complementary modalities.

Constructivist theory complements multimodal teaching by emphasizing active, hands-on learning experiences that facilitate knowledge construction across multiple representational formats (Alam, 2017). Social semiotics, drawing on Halliday (1978) and elaborated by Kress and van Leeuwen (2001), examines how diverse communicative modes—visual, auditory, gestural–shape meaning-making within social and cultural contexts. These perspectives align with UDL's principles of varied representation, expression, and engagement (Rose & Meyer, 2002).

https://doi.org/10.33225/BalticSTE/2025.71

Kress (2009) defines multimodal learning as constructing meaning through multiple semiotic channels. It involves the intentional integration of visual, auditory, kinesthetic, and textual elements to meet diverse learner needs and foster active participation. Multimodal instruction, therefore, strategically utilizes varied resources to enrich teaching and enhance learning outcomes (Theresia and Recard, 2021).

Teacher Education and Professional Development

Teacher education and professional development are critical for enhancing instructional quality and improving student outcomes. These processes encompass initial teacher training and ongoing professional learning, supporting reflective practice and continuous growth. Pre-service education provides future teachers with foundational knowledge, classroom skills, and confidence to address diverse learners (Rodriguez & Walters, 2017). Conversely, professional development for in-service teachers focuses on refining existing practices and adopting innovative strategies to enhance learning environments.

Amhag et al. (2019) emphasize the role of teacher educators in modeling subject-specific digital strategies to build motivation and pedagogical competence. Avalos (2011) notes that professional development is dynamic, supporting teachers' evolving roles over their careers.

Ongoing training across professions is essential to adapt to changing demands. In education, collaboration between novice and experienced teachers fosters improved instructional practices and student achievement (Vinesh, 2014).

While pre-service training typically emphasizes foundational skills like lesson planning, classroom management, and inclusive pedagogy, in-service teachers face challenges such as career stagnation, personal commitments, and systemic pressures (Hogg et al., 2023). Their professional development must address these complexities by promoting self-awareness, resilience, and instructional excellence.

Theoretical Framework

This study's theoretical framework is grounded in social semiotics. Kress (2009) highlights how multimodality enables learners to express diverse perspectives through multiple forms of communication, facilitating inquiry and meaning-making. Sociocultural theory, particularly Vygotsky's (1978) concept of mediation, views multimodal resources as essential learning tools that foster children's schema development, creativity, and inquiry.

Multimodal resources encompass linguistic expressions, gestures, actions, movements, sounds, tactile experiences, and culturally significant symbols. The study adopts the Multimodal Creative Inquiry (MCI) framework by Kewalramani and Veresov (2021) to guide analysis.

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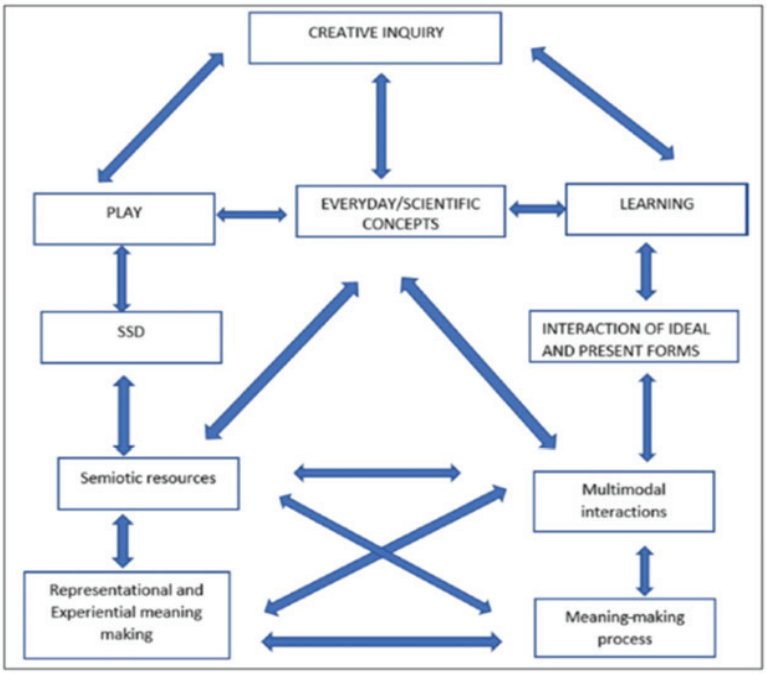
Figure 1
Multimodal Creative Inquiry Approach



Note: Kewalramani & Veresov (2021)

Multimodal Teaching

Multimodal teaching positively impacts educational outcomes by engaging students and addressing diverse learning preferences (Almumen, 2021; Tiba et al., 2015). For example, digital storytelling fosters voice, self-expression, and collaborative learning (Tiba et al., 2015). Integrating multimodal texts into literacy education enhances students' ability to use varied modes in lesson planning (O'Brien et al., 2018).

Strategies include visual aids (images, diagrams, videos), auditory methods (lectures, podcasts), kinesthetic activities (movement, hands-on tasks), text-based formats, and technology-driven tools (multimedia, simulations). Interactive simulations offer dynamic learning experiences that boost engagement (De Jong et al., 2021), while concept maps support organization and linking of information (Novak & Cañas, 2006). Multimodal teaching aligns with Project-Based Learning, Flipped Classroom, Collaborative Learning, Technology Integration, and STEM/STEAM education.

Evidence shows improvements in comprehension, retention, motivation, engagement, critical thinking, and problem-solving with multimodal methods. Students taught through multimodal approaches often grasp complex concepts better than those taught via traditional lectures (Ainsworth & Van Labeke, 2002). Similarly, multimedia tools correlate with increased motivation and participation. Also, media environments engage students in learning activities (Liu et al., 2011). However, effective integration

https://doi.org/10.33225/BalticSTE/2025.71

depends on teacher preparedness. Pre-service teachers often face barriers such as limited digital access and difficulty integrating tools (Haryyadi & Rohmah, 2023), highlighting the need for robust training and support.

Research Problem

In today's digital era, communication spans multiple modes and formats. Generation Z students, born mid-1990s to early 2010s, are digitally fluent, multitask effectively, and prefer digital learning environments. Their shorter attention spans and digital preferences challenge educators to adapt teaching methods accordingly. Multimodal instructional strategies, integrating visual, auditory, kinesthetic, and technological modes, are essential to engage these learners (Kress, 2009). These approaches accommodate diverse learning styles, deepen comprehension of complex concepts, and enhance student engagement.

This study investigates the implementation of multimodal teaching in STEM education, focusing on pre-service and in-service teacher training to better prepare educators for digitally native learners.

Research Focus

Multimodal teaching emphasizes comprehension and meaning-making through diverse semiotic resources: language, images, music, sound, movement—that contribute to discourse, design, production, and distribution in education (Jewitt, 2008; Nørgaard, 2009).

These modalities support knowledge construction and retrieval, extending beyond primary to higher education by fostering 21st-century skills and connecting learning to regional cultural wisdom (Baharudin, 2010; Nesi et al., 2010).

In STEM, multimodal resources enhance vocabulary, writing, and oral comprehension by integrating visual, auditory, and interactive elements. Kress (2009) notes that multimodal learning combines visual, auditory, gestural, spatial, and linguistic communication to create dynamic learning environments.

This study explores how embedding multimodal teaching strategies in professional development improves STEM instructional practices among pre-service and in-service teachers.

Research Aim and Questions

This research explores the integration of multimodal teaching strategies among in-service and pre-service STEM educators. Drawing on current literature, it examines the theoretical foundations and practical significance of multimodal instruction in diverse, digitally driven classrooms. The study aims to highlight the potential of this approach to address varied learning styles, enhance comprehension of complex concepts, and foster engagement.

Using qualitative methods, data were collected via group presentations, semi-structured interviews, and feedback forms to understand the effectiveness and challenges of multimodal teaching in STEM education.

https://doi.org/10.33225/BalticSTE/2025.71

1. How do multimodal teaching approaches influence the pedagogical practices and perceptions of in-service and pre-service STEM educators?
2. What challenges and opportunities arise during the implementation of multimodal teaching strategies in STEM education?

Research Methodology

Background

The workshop was designed for pre-service and in-service teachers to address diverse learning styles by encouraging active, hands-on participation. Engaging multiple senses, such as sight, sound, and touch, aimed to increase learner engagement, improve information retention, and reveal each learner's unique strengths. This approach also shifted the classroom dynamic from teacher-centered to student-centered learning, fostering self-confidence and autonomy.

Key activities included role play and play dough model making. In the role play, groups discussed scientific concepts, assigned roles, developed scenarios, and performed the plays collaboratively, emphasizing cooperation and shared responsibility. In the play dough activity, participants created scientific models using simple, biodegradable ingredients such as wheat flour, food colors, water, and oil and presented them, making learning interactive and enjoyable.

The training sessions sought to strengthen foundational knowledge, fill gaps, and enhance practical teaching skills through experiential learning. Workshops aimed to motivate ongoing professional development by introducing innovative teaching methods and improving job-related competencies.

Two one-day workshops were conducted prior to the academic year: one in Panvel, Maharashtra, India, for primary and secondary teachers across subjects, and another in Kuching, Sarawak, Malaysia, for second-year teacher trainees before their practicum. The program was designed to engage in-service teachers, who might otherwise view training as routine, while also supporting the enthusiasm of pre-service teachers eager for professional growth.

Sample

The study involved two distinct participant groups. The first group comprised 34 in-service teachers from Panvel city, India, who taught both primary and secondary classes across various subjects and had varying levels of teaching experience. The second group consisted of 56 pre-service teachers from Malaysia, who were undergoing foundational training without subject specialization, preparing to become future educators.

The Indian group's familiarity with local syllabi and teaching methodologies provided contextual depth, while understanding the Malaysian group's general syllabus framework and teaching-learning systems was necessary due to their different educational context. Participants were selected through purposive sampling based on voluntary participation and feasibility within the scope of international collaboration. Though not statistically representative of all teachers in either country, the sample was chosen to reflect a mix of experience and educational levels relevant to the study's qualitative

https://doi.org/10.33225/BalticSTE/2025.71

aims. The focus was on exploring perceptions, beliefs, and responses to multimodal educational strategies, offering valuable insights rather than broad generalizations.

Training duration differed to accommodate participants' commitments and motivations. In-service teachers, managing heavy workloads, attended sessions lasting one and a half hours with a brief break. Pre-service teachers, eager to develop their teaching skills, participated in longer sessions of three hours with an extended lunch break. The scheduling was carefully aligned with academic calendars and examination periods to maximize participation.

Instrument and Procedures

Data were collected through feedback forms, presentation notes, and semi-structured interviews to understand participants' experiences with multimodal teaching strategies. Feedback forms captured perceptions of the training, relevance of strategies, confidence in using them, and suggestions for improvement.

During group activities, participants designed and presented teaching models using play dough and role-play. Groups documented their planning, objectives, and reflections in presentation notes, which were analyzed to explore how multimodal approaches were applied collaboratively.

Semi-structured interviews with 15 purposely selected participants (9 in-service, 6 pre-service) provided deeper insights into challenges, impacts, and transferability of strategies. Interviews lasted 20–30 minutes and were recorded with consent. These instruments were previously validated and tested for reliability (Deshmukh et al., 2022).

Data Analysis

This descriptive qualitative study examined the impact of multimodal teaching strategies on in-service and pre-service STEM teachers. Content analysis was employed to analyze diverse data types, including feedback forms, presentation notes, and semi-structured interview transcripts. This method was chosen for its suitability in interpreting both verbal and nonverbal data (e.g., drawings, gestures) and its flexibility in addressing varied research questions (Figgou & Pavlopoulos, 2015).

Research Results

The analysis of data collected from group presentations, interviews, and feedback forms revealed several key themes reflecting the participants' experiences with multimodal teaching strategies: Multimodal teaching engages students through multiple communication modes such as text, visuals, audio, and video, enhancing the learning experience. Pre-service teachers found that multimodal strategies improve student engagement and understanding by addressing different learning preferences. They also felt more confident using technology to create interactive STEM lessons. The findings highlight the importance of preparing future educators with multimodal skills to meet current educational needs and support deeper learning in STEM.

https://doi.org/10.33225/BalticSTE/2025.71

In this study, a play dough activity helped teacher trainees visualize the shape, size, and position of diagram parts in human body systems. Creating models with play dough supported memory of the system's components, sequence, and proportions by engaging multiple senses, thereby enhancing long-term retention. Participants were divided into six groups, each assigned a human system theme such as Digestive, Respiratory, Nervous, or Excretory systems. Using textbooks or online resources, groups collaboratively crafted models and explained their assigned system. Feedback was positive, with participants enjoying the hands-on learning experience.

According to the participants:

"This activity will help students to develop interest in the topic and will help them remember the topic for a long time, maybe forever…"

"It is very interesting. We will get all the material easily. Our students otherwise cannot afford play dough from the market."

"This play dough is environment friendly, no harm even if consumed by mistake..."

The role play activity was modeled after a popular long-running health awareness TV program featuring an interviewer and doctors discussing a specific disease. Viewer questions were also included to enhance engagement.

For the session, 34 teachers were divided into six groups (five groups of five teachers and one group of four). Each group was assigned a disease theme such as Blood Pressure, Diabetes, Gastrointestinal diseases, Respiratory diseases, Cancer, or Cardiac diseases. They had 30 minutes to prepare, discussing and deciding roles: interviewer, doctors, and patient/viewers. Interviewers asked syllabus-based questions, doctors answered, and patient/viewers asked additional questions.

During the presentations, groups performed one at a time in a setup mimicking the TV program. Each had 20 minutes to cover most syllabus topics related to their disease. The teachers enthusiastically embraced their roles as presenters and actors, with the goal of replicating this engaging approach in their own classrooms.

The participants' response:

"This was a boring topic to teach in the classroom. I think students would do the role play activity with interest and will remember the topic very well."

" It's going to be fun in the class as students will learn the topic and will get the opportunity to explore their hidden talent."

Similarly, the role play activity for B.Ed. students followed the same arrangements as for in-service teachers. Each group was assigned an animal system, and each member took on the role of an organ within that system. Participants had to explain and defend the importance of their assigned organ's role in the system's functioning. After a debate, the group concluded that the system works effectively through coordination and harmony among all organs. Students were given 30 minutes to prepare, and during the presentation, they described the structure and function of their respective organs.

https://doi.org/10.33225/BalticSTE/2025.71

" Students can be taught without forcing them to study. This will enhance the process of teaching and learning."

Challenges in Implementing Multimodal Teaching Approaches

From feedback forms and semi-structured interviews, most of the participants shared their views as below-

A pre-service teacher from Malaysia shared -.

"*I understand the value of using different modes to teach – like visuals, hands-on models, and videos – but honestly, we just don't have enough resources. At my practicum school, the internet connection is weak, and there aren't enough devices for students,"*

This reflects a widespread challenge regarding limited access to digital applications and infrastructure needed to support multimodal instruction.

Another participant shared her views as -

"Even when tools are available, I often don't have enough time to plan or explore new strategies,"

As the rigid lesson planning requirements and exam-focused curricula leave little room for innovation or experimentation with alternative teaching methods.

A participant from Malaysia shared her experience as - *"It's not just about time or tools, creating lessons using multiple formats–visuals, audio, and physical models—takes more effort than traditional methods. You need to think about how everything fits together. That takes skill, and we're still learning."*

It reflects the concern about the technical and planning demands involved in designing effective multimodal experiences.

An Indian in-service teacher added - *"Assessment is another headache. How do I evaluate learning fairly when some students respond better to visuals while others prefer discussion or physical activities?"*

It's challenging to find a single multimodal teaching approach that works effectively for all learners.

These narratives underscore the urgent need for teacher education programs to scaffold pre-service teachers with more technical training, resource access, and flexibility. Without such support, many capable future educators may hesitate to adopt multimodal strategies–even when they recognize their potential.

https://doi.org/10.33225/BalticSTE/2025.71

Discussion

This study demonstrated that multimodal teaching strategies significantly influence both in-service and pre-service teachers' engagement, instructional creativity, and learner-centered pedagogical approaches in STEM education. Grounded in social semiotic theory, multimodal teaching encourages meaning-making through multiple modes–textual, visual, auditory, kinesthetic–within social and cultural contexts (Kewalramani & Veresov, 2021). Participants' experiences with play dough modeling and role-play not only made abstract STEM content more tangible but also fostered collaboration, expression, and critical thinking, reflecting the potential of the Multimodal Creative Inquiry (MCI) framework in practice.

Impact on In-Service and Pre-Service STEM Teachers

The study confirms earlier findings that effective teacher training in multimodal pedagogy enhances confidence, technical skill, and classroom application (Greene, Cheng & Jones, 2023; Diamah et al., 2022). Pre-service teachers reported a stronger sense of preparedness when given opportunities to engage in hands-on, collaborative learning activities. Techniques like role-play—where participants embodied parts of human or animal body systems—and tactile modeling with play dough facilitated not only content mastery but also pedagogical reflection. These multimodal experiences directly supported a shift from didactic to student-centered approaches, which aligns with constructivist learning principles that emphasize active knowledge construction (Vygotsky, 1978).

Teacher educators must design programs that go beyond theoretical instruction by incorporating active learning methods and digital integration. This resonates with Alcántar (2024), who found that combining ICT with experiential learning improves teaching efficacy. However, as Alcántar also cautions, implementing complex strategies such as gamification or flipped classrooms demands not only conceptual understanding but also technical agility and pedagogical competence—areas where ongoing support is needed.

The findings also support Bandura's (1977) theory of self-efficacy, as participants' increased confidence stemmed from mastery experiences during the workshops. These structured opportunities helped bridge the theory-practice gap and enhanced pre-service teachers' readiness to implement multimodal strategies in real classrooms.

In-service teachers reported similar benefits. Engaging in activities like mock interviews for health education themes stimulated creative instructional approaches and rejuvenated their teaching practices. This mirrors Singh and Sarma's (2025) conclusion that continuous professional development invigorates teaching and can lead to instructional transformation.

Challenges and Opportunities in Implementing Multimodal Approaches

Despite the benefits, significant barriers persist. Participants reported constraints related to infrastructure, time, and technical proficiency. For instance, some pre-service teachers from Malaysia cited unreliable internet and insufficient digital devices, limiting

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their capacity to fully leverage digital tools–a concern also raised by Jere & Mpeta (2024). Even when tools are available, teachers often lack the time or training to design and integrate multimodal content effectively, echoing the challenges highlighted by Tiba et al. (2015) and Marfuatun et al. (2024). The need to design cohesive multimodal experiences that engage various learner preferences also places a cognitive and logistical burden on teachers.

Assessment was another key concern. Teachers expressed uncertainty about how to fairly evaluate students in multimodal environments where responses vary across visual, verbal, and kinesthetic modes. This underscores the importance of equipping educators with inclusive assessment strategies, an area where teacher education programs must provide explicit guidance (Marfuatun et al., 2024).

Despite these challenges, the enthusiasm and creativity displayed by participants indicate a strong potential for multimodal methods to transform STEM classrooms. When provided with appropriate support and resources, teachers can implement strategies that not only increase engagement but also foster deeper conceptual understanding, consistent with cognitive load theory (Sweller, 1988) and research on multiple representations in science learning (Treagust & Tsui, 2013).

Toward Inclusive and Student-Centered Classrooms

The role-play activities revealed how multimodal teaching supports collaborative and inclusive learning environments. By encouraging learners to embody and articulate knowledge through diverse formats, these strategies cater to different intelligences and learning styles. This aligns with Tomlinson's (2014) advocacy for differentiated instruction and inclusive pedagogy. Moreover, the use of sensory-rich, playful methods–such as modeling body systems with play dough–demonstrated how active learning supports memory retention and makes abstract concepts concrete (Prince, 2004).

These findings reaffirm that multimodal strategies are not only pedagogically sound but also socially responsive, offering equitable pathways for diverse learners to access and express their understanding. As digital and physical learning environments continue to evolve, preparing both pre-service and in-service teachers with adaptive multimodal competencies is essential for meeting the demands of 21st-century STEM education.

Conclusions and Implications

This study underscores the transformative potential of multimodal teaching approaches in STEM education, particularly when integrated within professional development programs for both pre-service and in-service teachers. Multimodal strategies not only enhance learner engagement and comprehension but also empower educators with digital pedagogical skills vital for contemporary classrooms.

While positive outcomes were evident, practical challenges such as resource availability and teacher workload must be addressed to optimize implementation. Educational institutions and policymakers should prioritize sustained support, infrastructure development, and capacity building to foster the widespread adoption of multimodal instructional practices.

https://doi.org/10.33225/BalticSTE/2025.71

Future research could expand on longitudinal impacts of multimodal teaching on student achievement and explore scalable models of professional development that integrate multimodal pedagogy effectively.

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Declaration of Interest

The authors declare no competing interest.

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THE ROLE OF LEADERSHIP IN CURRICULUM TRANSFORMATION: IMPLICATIONS FOR SCIENCE, TECHNOLOGY, ENGINEERING, ARTS AND MATHEMATICS IN HIGHER EDUCATION

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Abstract

Leaders in Higher Educational Institutions (HEIs) worldwide are confronting multifaceted challenges. The aim of the research was to explore the role of leadership in curriculum transformation, and the implications of this for Science, Technology, Engineering, Arts and Mathematics (STEAM) in Higher Education (HE). An inductive, interpretivist research adopting a qualitative approach was employed. Thirty participants were purposively selected to participate in a hybrid workshop. Nineteen participants were engaged in Science, Technology, Engineering, and Mathematics (STEM) and eleven in Management. Data was generated from participants' responses relating to leadership problems experienced in effecting curriculum transformation, and how leadership impedes and enables transformation. Findings revealed that communication, bureaucracy, and resistance to change are critical for leaders in effecting curriculum transformation and the introduction of STEAM. Leadership in HEIs can enable transformation by providing support, direction, motivation, funding, and engaging with staff. Effective leadership in STEAM education plays a pivotal role in curriculum transformation and guiding academics and students towards an integrated and holistic approach to science education. Since leadership in STEAM education is essential for fostering innovation and creativity in HEIs, their provision of support, direction, motivation, funding, and engagement with staff, is critical.

Keywords: *curriculum transformation, higher education, higher educational institutions, leadership in STEAM, STEAM*

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Introduction

Globally, Higher Educational Institutions (HEIs) are operating in a volatile, uncertain, complex, and ambiguous (VUCA) environment (Bennett & Lemoine, 2014) where they are confronted by a variety of challenges (James et al., 2025; Gerwel Proches et al., 2025). The challenges include the need for relevance and adaptability, globalization, technological integration, financial constraints, and evolving expectations from staff and students (Lemoine et al., 2017; Waller et al., 2019). The COVID-19 pandemic accelerated the need for HEIs to restructure, particularly in terms of curriculum design and development (Berthoud et al., 2021; Waldeck et al., 2024).

The study is part of the DECART project (Designing Higher Education Curricula for Agility, Resilience, and Transformation). The DECART project involves six HEI partners from France, Germany, Lithuania, Iceland, Indonesia, and South Africa. There are three work packages in the project, focusing on curriculum design, resilience, and transformation.

Research Problem

Science, Technology, Engineering, Arts, and Mathematics (STEAM) education has emerged as a pivotal approach for future-ready learning. While both Science, Technology, Engineering, and Mathematics (STEM) and STEAM emphasize scientific concepts through inquiry and problem-based learning, STEAM uniquely incorporates the arts, fostering creativity alongside technical proficiency (Carter et al., 2021). This integration should encourage risk-taking, collaborative and experiential learning, and perseverance in problem-solving, aiming to cultivate future leaders, innovators, scientists, engineers, educators, entrepreneurs, and lifelong learners.

The inclusion of the arts in STEAM is designed to enhance creativity (Razi & Zhou, 2022) – a skill identified by the World Economic Forum as one of the top three skills required for the future workforce (World Economic Forum, 2016). As people navigate the Fourth Industrial Revolution (4IR), characterized by breakthroughs in artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3D printing, and biotechnology, the demand for a workforce that is not only technically adept but also creative and innovative has become paramount (Penprase, 2018). Developing such a skill set necessitates curricular reforms and the provision of diverse programs and projects that offer teachers and learners opportunities to engage with various approaches and strategies, thereby fostering the competencies essential for success in this rapidly evolving landscape (Schwab, 2024). It is argued that "Substantial changes to the science and technology curriculum will be required to allow for students to develop capacity in the rapidly emerging areas of genomics, data science, AI, robotics and nanomaterials" (Penprase, 2018, p. 217).

STEAM with A for arts has been conceived as an alternative to STEM pedagogy helps students develop a well-rounded skill set and to promote creativity. Creativity, an important skill, is placed "third out of 10 skills needed for the future of work" (World Economic Forum, 2016, p. 21). Creativity is one of the most important job skills that companies are currently looking for and what is needed to succeed in the 4IR (Penprase, 2018; Shatunova et al., 2019). The 4IR is the technology breakthroughs in fields such as

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artificial intelligence, robotics, the Internet of Things, autonomous vehicles, 3-D printing, biotechnology, etc. (Penprase, 2018). Therefore, the workforce that is required needs to have new ways of thinking, be digitally competent, creative, understand technical topics, and also apply creativity in innovative ways to reshape our future (Shatunova et al., 2019). The development of this skill is possible with changes in the schooling curriculum and opportunities for teachers and learners through various programmes, projects, etc., using a variety of approaches and strategies (Penprase, 2018).

Research Focus

Despite global initiatives to advance STEM education, numerous scholars contend that achieving this objective remains challenging (da Costa, 2019; Osborne & Dillon, 2008). This difficulty may stem from teachers' need for a solid content knowledge base in the subjects they aim to integrate (English, 2017; Kim & Bolger, 2016). Therefore, it is essential to offer teachers professional development programs (PDPs) that equip them with the necessary knowledge and skills to meet these goals. Developing effective PDPs involves creating collaborative workshops where teachers can practice the methods they are expected to implement in the classroom (Afonso et al., 2005). To promote an integrative STEM teaching and learning approach, it is crucial to provide teachers with opportunities to deepen their understanding of mathematics and science content (Ríordáin et al., 2016). These authors also emphasize that school-level support is vital for the successful adoption of integrative methods. Ultimately, PDPs are effective only when teachers acquire the skills to apply their learning in classroom settings (Buczynski & Hansen, 2010).

McCauley and Fick-Cooper (2024, p. 2) have defined "leadership as a social process that enables individuals to work together to achieve results that they could never achieve working alone". Drath et al. (2008) have argued that there are two types of leadership ontology – the tripod and DAC (Direction, Alignment, and Commitment) – which may guide a researcher. First, the tripod ontology of leadership entails leaders, followers, and common goals. Drath et al. (2008, p. 635) have argued that the tripod "is an expression of commitment to the entities (leaders, followers, common goals) that are essential and indispensable to leadership and about which any theory of leadership must therefore speak". The tripod is explicit that it is erroneous to define leadership without focusing on the interactions between the leader, follower, and common goal with full recognition that leadership is about what people do together, rather than what a leader does or the capabilities he or she has. However, the criticism of understanding leadership as a tripod is that it emphasises the dyadic and hierarchical influence of a leader on followers, but is silent on the lateral influence of peers and external stakeholders (Drath et al., 2008).

Second, the DAC ontology of leadership is distinctive because it acknowledges the need for a clear shared direction, alignment, and commitment whether in a group, department, or organisation to achieve the common goal (Drath et al., 2008). The direction as a leadership outcome is characterised by widespread agreement on vision, mission, objective, and what the leader and followers are trying to accomplish together. One of the key functions of leadership is to communicate the vision and clear direction to followers (McCauley & Fick-Cooper, 2024). For example, transformational leaders

https://doi.org/10.33225/BalticSTE/2025.86

champion the integration of innovative teaching methods and advanced technologies, such as artificial intelligence, virtual reality, and data analytics, to enhance learning experiences.

The other leadership outcome is alignment – which refers to the effective organisation and coordination of knowledge and work in a collective in service of their shared direction. To achieve results, aligning diverse individuals and groups to work together towards shared goals and objectives is a key function of leadership. Effective alignment requires that everyone knows what they are doing and why, what is happening in other parts of the organisation, and how their work connects with others (McCauley & Fick-Cooper, 2024). Building and developing others is another key function of leadership in pursuit of short and long term objectives. Modeling the way is a key function of leadership, especially in that it provides signals to what is expected and appropriate (or not) in the collective.

Lastly, commitment as a leadership outcome underscores the willingness of members of a collective (team, taskforce, department, entire organisation) to subsume their own interests and to prioritise the collective interest (Drath et al., 2008). Leadership has the function of engaging the human element of the organisation, not only to achieve goals and objectives but also to build and develop individual and the organisation`s future capacities. DAC as a way of understanding leadership moves beyond the idea of dyadic influence between leaders, followers, and shared goals, as it states that leadership happens when there is multiple social influence and groups of people are producing direction, alignment, and commitment (McCauley & Fick-Cooper, 2024). Given the Tripod and DAC ontologies of leadership, Covey (2021) has summarised that the four essential roles of leadership are creating a shared vision and strategy and communicating it powerfully so that others join on the journey; inspiring trust to build teams which achieve results, developing the potential in others and the organisation to improve performance; and translating strategy into actions and results with and through others in an aligned organisational environment which focuses on what is most important and makes it easier to get work done (Covey, 2021).

It is prudent that research on leadership and curriculum transformation not only focus on the dyadic social influence and interactions of the leader, follower, and pursuit of common goals. In pursuit of the common goal of curriculum transformation within STEAM education in HEIs, it is essential that scholars seek to understand the roles and functions of leadership, and how leaders and various stakeholders agree on the collective`s shared direction, align for effective coordination of work in service of the shared direction and ensure strong commitment of various stakeholders to prioritize the success of the collective.

The DECART project is about STEM and Management. But, for the purposes of this paper, the focus is on STEAM, as this is the progressive development from STEM, which includes the Arts. Many studies on STEAM have employed quantitative methods (Neldarisasmita et al., 2025), and a qualitative method is employed here. A gap is present in the literature on effective leadership models that can support STEAM education (Zarei et al., 2024). This study offers pertinent aspects to be considered in leadership in the context of STEAM. Furthermore, leadership in STEAM during the VUCA contexts is considered.

https://doi.org/10.33225/BalticSTE/2025.86

Research Aim

The aim of the study was to explore the role of leadership in curriculum transformation and thereby derive implications for STEAM in HE.

Research Methodology

General Background

This exploratory, qualitative study used an interpretivist paradigm, given that it was considered suitable to gather multiple and subjective views of participants (Cohen et al., 2018) on the role of leadership in curriculum transformation, in STEM education. The workshop was held in hybrid mode and lasted two hours.

Sample

Census sampling was used to get thirty academics working in the field of STEM and Management with expressed interest in curriculum transformation in HE. The academics were between the ages of 35-60 years. Fourteen were male and sixteen females. Two French, two Lithuanian, four Indonesian, one Icelandic, one German, two Zimbabwean, two Latvian, and 16 South Africans participated in the study. Nineteen academics in this study were engaged in STEM (Engineering, Physics and Chemistry, Mathematics, Computer Science, Life Sciences) and 11 in Management (Business Studies, Economics). Of these participants, 14 in total were members of the DECART project.

Instrument and Procedures

The participants were invited to participate in a workshop exploring the role of leadership in curriculum transformation. A set of three reflective questions was prepared using Mentimeter. Mentimeter is an interactive, real-time polling digital tool, which provides participants with an opportunity to share their views (up to three responses can be added per participant), and also their responses can be collectively shown and observed. The three reflective questions were: *1. What leadership problems are experienced in effecting curriculum transformation, 2. How does leadership impede transformation, and 3. How does leadership enable transformation?* The participants' responses were captured using Mentimeter. The workshop and the tools employed, are aligned with the interpretive paradigm, which seeks multiple perspectives. Ethical clearance was obtained from the University of KwaZulu-Natal to conduct the study.

Some participants joined the workshop via Zoom, and others were in person. Participants worked in groups; three groups in person, and one online group. Groups were formed by allocating a number (1, 2, or 3) to each participant in the physical room. Participants engaged in discussions on their responses to the three questions presented to them.

https://doi.org/10.33225/BalticSTE/2025.86

Data Analysis

The workshop was recorded, onsite and online, and transcriptions obtained. Data were analysed using thematic analysis. This involved breaking down transcribed data into labels, which were subsequently compared to each other to get patterns. The identified patterns reveal similar themes relevant to this study.

Research Results

First, the results reflect the responses to the three questions as observed on the different Mentimeter screens, and then the themes. Figures 1, 2, and 3 provide the responses to the Mentimeter.

Responses to the three questions as shown on the three Mentimeter screens.

Figure 1

Leadership Problems Experienced in Effecting Curriculum Transformation

Participants highlighted that the main leadership problems that were experienced in effecting curriculum transformation, as per Figure 1, were communication and bureaucracy. Other responses included change management, resistance to change, inflexible system, policy constraining, insufficient funding, lack of skills, lack of interest, no motivation, and divergent points of view.

https://doi.org/10.33225/BalticSTE/2025.86

Figure 2
Leadership Factors Impeding Curriculum Transformation

As per Figure 2, participants mentioned resistance to change as a key way in which leadership impedes curriculum transformation. Other responses include being closed to alternatives, top down decision-making, slow decision-making, slow feedback, control, bureaucracy, restriction, rigidity, detachment, resource constraints, lack of vision, stubbornness, political barriers, and lack of EQ (Emotional Quotient / Emotional Intelligence).

Figure 3
Leadership Factors Enabling Curriculum Transformation

Enablers, as highlighted in Figure 3, include engagement, funding, support, providing direction, having a clear vision and strategy, motivating stakeholders, and having resources. Other responses include being helpful, encouraging, forward-thinking, professionally developed, and providing academic support.

Themes

Complexities of Curriculum Transformation

The results revealed that curriculum transformation is a complex process impacted by bureaucratic inefficiencies, slow decision making, leadership styles, resource constraints, multi-level systemic factors, and political contexts. Participants noted how critical agile decision-making, visionary leadership, and a strategic approach that balances internal and external demands is to ensure curriculum transformation.

"... the problem we identified firstly is lack of communication. So, communication inhibits curriculum development."

Participants identified several factors that contribute to slow decision-making, including a lack of deadlines, insufficient discussion, and the tendency to "put on the back burner" important issues. The lack of "feedback on an idea and a creative aspect" further impedes the process of change. The need for "training in project management" was suggested as a potential solution to improve decision-making efficiency.

The findings revealed that bureaucratic centralized control limits diverse perspectives and stifles innovation. When a small group holds exclusive power, it creates an environment where alternative ideas are suppressed, and change is perceived as a threat to their authority. This limited input creates an environment where those outside of the small group feel that their voices are not heard. The data revealed a consistent theme: bureaucracy, characterized by centralized control and limited collaboration, fosters resistance to change by creating a disconnect between policy and practice.

"And so policies and procedures are made, but not in the understanding of what is actually happening on the ground level."

Centralized decision-making, bureaucratic hurdles, and slow feedback loops further exacerbate the resistance, making it difficult to implement necessary reforms. Political barriers and detachment from on-the-ground realities also hinder transformation efforts, emphasizing the need for adaptive leadership and proactive engagement with stakeholders.

When staff and faculty are excluded from decision-making, they feel disengaged and uninvested in the outcomes. This lack of buy-in creates a natural resistance to change, as individuals are less likely to support initiatives they had no part in shaping. It also can create a knowledge deficit, where the small group making the decisions do not have all of the needed information.

Creating Conducive Systems

The results shed light on how structural and systemic issues within HEIs also play a pivotal role in shaping the trajectory of curriculum transformation. Participants emphasized the importance of aligning organizational structures, systems, and procedures with the goals of change. This highlights the necessity of creating a supportive organizational framework that facilitates rather than obstructs change.

https://doi.org/10.33225/BalticSTE/2025.86

"So, to implement something, there's a need to look at the structure, the organizational structure, the hierarchy, the arrangement of different elements. Because change may become difficult because probably there's no structure appropriate for that. And then you have to look at the systems, the processes, and the procedures of how work is going to be done, you know, and how decisions are going to be made."

A recurring theme is the need to shift from traditional power dynamics in education. The critique of "top-down" approaches to curriculum development and the call for "joint engagement" reflect a desire to democratize the educational process. The recognition that "we as academics are not the ones to be disseminating knowledge from a power perspective as knowers" underscores the need to embrace a more collaborative and student-centered approach to teaching and learning. The acknowledgment that "you are silenced" within institutions highlights the power imbalances that can hinder open dialogue and critical reflection. The call for educators to "share honestly" and "courageously" reflects a desire to create a more equitable and inclusive educational environment.

Resistance to Change

It was highlighted that a critical inhibitor of curriculum transformation is resistance to change, particularly among faculty members. The discussion identifies that resistance may stem from various stakeholders, including lecturers, students, and industry partners. Factors contributing to this resistance include traditional mindsets, lack of motivation, and fear of disrupting established curricula. It was argued that there is a need for strategic leadership that motivates stakeholders and fosters a culture of adaptability. Overcoming this challenge is important for ensuring that academic programmes remain relevant to evolving industry and societal needs. This theme underscores the importance of thoughtful and strategic change management.

"This is the essence of resistance to change. The people don't want to change. And if they don't want to change, they're going to forget about it. They're going to have a lack of a deadline. There's going to be a delay in taking action. So, the first question you have to really look at is How do we overcome resistance to change?"

"Resistance to change is something, but too many changes are another point. I think each time a leader comes in, he wants to change. And so, what's the purpose of changing for changing? Sometimes there is no purpose, real purpose."

Political barriers, detachment of leadership, and hierarchical decision-making structures further complicate the process. Attitudes toward change play a crucial role in determining the success of curriculum reforms. Some faculty members view change as unnecessary or disruptive, particularly when changes are frequent and lack clear objectives. The discussion raises concerns about the phenomenon of "change for the sake of change," where successive leadership transitions introduce new reforms without proper evaluation of previous initiatives.

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Leadership plays a pivotal role in navigating resistance to change. Ineffective leadership, lack of clear vision, and poor communication contribute to faculty and student resistance. Furthermore, escalating decisions to higher administrative levels or broadening the scope of ideas or implementation space can inadvertently suppress innovative ideas. Effective leadership requires balancing strategic oversight with grassroots involvement. Leaders must actively engage faculty and students in decision-making, fostering a sense of ownership over the change process.

The study findings also highlighted a perceived disconnect between curriculum content and real-world applications. Resistance arises when curriculum changes do not align with industry needs or fail to consider student perspectives. The discussion suggests that elitism in academia, coupled with rigid disciplinary boundaries, limits the practical relevance of curricula. Engaging students, industry professionals, and community stakeholders in curriculum development can enhance relevance and reduce resistance.

The long-term nature of change was also raised as a concern. Resistance to change is not a short-term issue but an ongoing challenge in academic institutions. The discussion underscores that even after several years, HEIs may struggle to implement meaningful change. This highlights the need for adaptability, long-term commitment, sustained dialogue, and iterative approaches to reform.

"And the other big thing is, don't expect that this thing will work in one year, two years, five years, even 10 years down the line. We'll be sitting here, and we'll be having the same conversations that we would have moved just an inch. So, we're always fighting against this wave."

Leadership and Organisational Culture

Participants highlighted the "big, big elephant in the room," which referred to leadership and management styles. Mention was made of slow decision-making, which suggests a need for more decisive and proactive leadership. The call for quick decision-making reflects a desire for greater agility and responsiveness in the curriculum transformation process. Participant responses indicate that the effectiveness of curriculum transformation is closely tied to leadership styles and management systems.

"So, when making change, you need to look at the structure, you need to look at the system. There was talk of style of, you know, leadership and style of management, which is within the organization, you know, trying to run away from making decisions or leadership style that is quick in making decisions, so on and so forth. That is also important."

"And I've learned over the years, if somebody says, oh, that's a brilliant idea. Let's not only do that in our faculty, let's get all the faculties on board. That is the quickest way to shoot something down. So, it already helps you if you have that awareness that these elegant tricks of escalating it up in the university will actually crush the whole idea."

The results reveal that it is critical to move beyond traditional, static curricular frameworks to embrace more dynamic and inclusive approaches. Leadership plays an important role in curriculum transformation by fostering collaboration among all relevant parties–faculty, students, community members, and industry experts. A top-

https://doi.org/10.33225/BalticSTE/2025.86

down approach often results in disengagement, whereas participative leadership creates an environment where knowledge is co-created rather than imposed. Encouraging discussions and negotiations with all stakeholders ensures that the curriculum reflects diverse perspectives and remains relevant to real-world needs.

Collaborative and Participatory Leadership

Participants highlighted the importance of collaboration in leadership. Responses indicate that leadership is not about imposing decisions but rather about actively listening, engaging with stakeholders, and fostering teamwork. Effective leaders in curriculum transformation must facilitate dialogue between faculty, students, administrators, and external partners to ensure that reforms are well-received. Participants noted that clear communication of goals, strategies, and expectations is essential for successful transformation. Without clarity and stakeholder engagement, even the most well-intended reforms may fail due to misalignment or lack of support. This theme aligns with participatory leadership, where decisions are made through inclusive discussions rather than being dictated by a single authority. Such an approach encourages ownership, accountability, and greater buy-in from all parties involved.

"... good group management, good leader who will hear every member of the group. Also, clear communication on the goals."

"So, a leader has to set a very good relationship, collaboration with all stakeholders, and also the ethics has to be there."

Strategy

Strategic deficiencies emerged as a significant impediment. Participants identified strategy itself as a problematic element, encompassing planning, goal achievement, and competitive advantage. The lack of a clear, well-communicated strategy, coupled with inadequate evaluation and monitoring, contributes to the challenges of curriculum transformation. The importance of data-driven decisions and continuous support was also raised, showing that a lack of strategic oversight hampers progress.

Strategic Leadership

Participants indicated that a strong vision is critical, which appears to be the backbone of transformational leadership. Leaders in education must not only articulate a clear vision for curriculum transformation but also ensure that this vision is supported by well-defined strategies, policies, and resource allocation. It was observed that key elements of strategic leadership, which include mission and vision clarity, resource management, policy development, motivation, and inspiration, are relevant in the discussion around curriculum transformation. Mission and vision clarity proposes that leaders must ensure that all stakeholders understand the direction of transformation. Resource management implies, financial, human, and infrastructural resources must be aligned to support the change. Concerning policy development, leaders must work within accreditation standards and educational policies to implement reforms effectively.

https://doi.org/10.33225/BalticSTE/2025.86

Finally, motivation and inspiration imply that leadership is not just about administration; it involves inspiring and motivating teams to embrace change and innovation. Without a strong vision and strategic planning, curriculum transformation efforts may lack direction, leading to fragmented and unsustainable changes.

"Leadership components as a vision, vision and mission strategy communication, then also resources that include financial resources… and maybe also infrastructure resources."

"They need certain skills, right, to be a visionary and to be able to set policy. And also, a leader has to have the ability to deal with the accreditation standard. And also, a leader has to have a motivation skill, has to be a motivator."

Inclusive, Inspirational, and Ethical Leadership

The results revealed that leaders must be inspirational and passionate, open-minded and inclusive, and accountable and transparent. Inspirational and passionate implies that leaders should not only manage change but also inspire confidence, trust, and motivation among faculty and students. Open-minded and inclusive implies inclusive leadership fosters diverse perspectives, equity, and broad participation in decision-making. Accountable and transparent leadership places the emphasis on monitoring and evaluation, indicating that curriculum transformation must be continuously assessed to ensure alignment with shared values and institutional goals. Networking and relationship-building also play a role in ensuring that transformation is not an isolated process but one that integrates diverse voices and perspectives. Ethical leadership ensures that curriculum changes address broader social and cultural dynamics, preventing exclusionary practices.

"And so, and hence the interpersonal skills that a leader has to have are inspirational to inspire all the stakeholders to follow the vision. And also, emotional skills as a leader has to have it, and also the passion and open-mindedness. And for the inclusivity, I think that we think that networking is very important."

Resilience in Leadership

The study findings indicated that resilience is a critical leadership trait in navigating curriculum transformation. The ability to adapt to change, manage uncertainties, and maintain persistence in the face of resistance is fundamental to successful leadership. The results emphasise that curriculum transformation is a continuous and often challenging process, requiring leaders to endure setbacks, opposition, and external pressures while maintaining focus on long-term goals. Leaders who demonstrate resilience can motivate their teams, sustain reform efforts, and navigate the complexities of institutional change more effectively.

"Resilience. I think it's very important when you look at leadership is, do you have resilience and staying power for the changes that are coming in? From whichever direction, resilience is the ultimate."

https://doi.org/10.33225/BalticSTE/2025.86

Discussion

Effective leadership in curriculum transformation is vital for alignment or coordination, and commitment of stakeholders is necessary to driving innovation, leading change, and cultivating environments that promote interdisciplinary learning and adaptability as part of curriculum transformation (Gerwel Proches, et al., 2025; Middlehurst, 2012). Effective leaders provide a clear vision and direction for curriculum transformation, ensuring that educational goals align with the demands of the modern world, such as innovation and technology adoption. Leadership is also crucial depending on the resilience process stage: when coping with a crisis, leaders are capable of agility in the decision-making process, facilitated by an organizational culture that favors continuous monitoring and improvement of key processes (Gardner Le Gars et al., 2023).

The study highlighted how communication is a pivotal element in the success of curriculum transformation efforts (James et al., 2025). A shared vision, participative leadership, epistemological access, structured governance, stakeholder- motivation, and cultural awareness collectively shape the transformation process. Effective communication fosters engagement, problem-solving, and buy-in, ultimately ensuring that curriculum changes meet the evolving needs of higher education institutions and society at large. To achieve meaningful and sustainable curriculum transformation, educational leaders must prioritize transparent, inclusive, and adaptive communication strategies.

Effective communication is at the heart of curriculum transformation, serving as a means of building trust, aligning teams, and ensuring clarity in expectations. The data suggests that leadership should adopt a two-way communication approach—both influencing and being influenced by team members (Daft, 2023). Clear, concise, and transparent communication fosters an environment where faculty and students understand their roles in curriculum reform. Moreover, effective communication enhances decision-making and ensures that all stakeholders feel valued in the transformation process.

The study findings emphasise the need for a leader who is a visionary capable of anticipation and preparation for both positive or negative future transformation impacting the organisation (Denyer, 2017). Overall, a leader engages the organization in a process of transformation based on organisational, anticipation, and learning capacities despite the resistance the organisation can oppose. Transformational leadership is critical in HE (Bohari et al., 2024). Transformational leadership is particularly significant in not only influencing followers towards a common goal (e.g., educators embrace new teaching methodologies, integrate advanced technologies, enhancing the learning experience) but also achieving DAC of educators to realise curriculum transformation. They cultivate a culture of continuous improvement and encourage experimentation with novel instructional strategies, which is crucial for the evolution (Al-Husseini et al., 2021; Budur, 2020; Delahunty & Kimbell, 2021) and the resilience of STEAM curricula (Waldeck et al., 2024).

The results point to how faculty members may resist change due to entrenched academic traditions, concerns about increased workload, and skepticism about new teaching methodologies. This has been highlighted in previous studies (Lane, 2007). Students and parents may also resist changes that alter familiar learning structures or

https://doi.org/10.33225/BalticSTE/2025.86

assessment methods. A key aspect of overcoming resistance is motivation. The study emphasizes the importance of engaging stakeholders by demonstrating the benefits of change. Institutional resistance is often exacerbated by bureaucratic structures, slow feedback mechanisms, and centralized decision-making processes. Top-down approaches to curriculum reform can stifle innovation and lead to delays in implementation (James et al., 2025).

Integrating STEAM education requires leaders to provide educators with the necessary training and support. Adapting curricula to include practical problem-solving and fostering an environment that encourages creativity and critical thinking are essential steps in this process (Santana & Bornay-Barrachina, 2024). By adopting transformational leadership practices, providing targeted professional development, and fostering supportive learning environments, leaders can effectively guide their institutions through the complexities of curriculum innovation.

It is clear that information gaps and communication breakdowns create significant obstacles to curriculum transformation. The lack of clear, consistent communication not only impedes the dissemination of information but also undermines trust and collaboration, both of which are essential for successful curriculum transformation. Overcoming these barriers requires a proactive approach, involving leadership buy-in, stakeholder motivation, and regulatory adaptability (Gerwel Proches et al., 2025). Penprase (2018, p. 225) argues that "Our colleges and universities owe it to these students and our future to develop more interactive forms of pedagogy at all levels…".

Stakeholder motivation is a critical enabler of curriculum transformation (James et al., 2025). Leaders must possess motivation skills to secure stakeholder buy-in. This involves marketing the proposed changes effectively and demonstrating their relevance to faculty, students, and external partners. Motivation is also linked to a sense of agency among educators, who should see themselves as active participants in shaping the curriculum rather than passive recipients of top-down directives. A collaborative approach fosters a sense of ownership and investment in curriculum changes.

There is a need for emotional intelligence in HE leadership (Daft, 2023). The findings highlight that leaders must foster empathy, social awareness, and effective communication to create a conducive learning environment. Leaders in curriculum transformation must therefore go beyond structural changes and policies; they must also cultivate meaningful relationships with students and staff. This requires a shift from rigid, top-down leadership to a more engaged, emotionally intelligent leadership style that prioritizes student needs, emotional well-being, and inclusivity in the educational process.

Leaders foster a culture of empowerment and collaboration, encouraging educators and students to actively participate in the transformation process and contribute their ideas. By promoting a mindset of continuous improvement, leaders help institutions adapt to changing educational landscapes and ensure that curricula remain relevant and effective. Investing in leadership training and development programs can help educators develop the skills needed to lead curriculum transformation efforts effectively. Fostering a mindset of quality culture by promoting collaboration, continuous improvement, and professional development has been proven to be properties increasing the resilience of a curriculum (Waldeck et al., 2024; Waldeck et al., 2025).

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Leadership development programs that include coaching can be especially effective in preparing future STEM leaders. They help leaders build the skills needed to manage curriculum changes and support faculty in adopting innovative practices (Okpala et al., 2021). A model developed for principals' STEM leadership capability emphasizes the need for discipline-specific knowledge, contextual understanding, and a disposition towards fostering innovation (Geiger et al., 2023).

Conclusions and Implications

The aim of the study was to explore the role of leadership in curriculum transformation and thereby derive implications for STEAM in HE. The study highlighted that a successful leader in curriculum transformation does not merely enforce policies; they engage, inspire, and strategically plan for meaningful change. The challenge lies in balancing institutional constraints with innovation, policy with practice, and vision with execution. An understanding of the complexities can help HEI leaders develop more effective strategies for navigating and leading transformation in higher education.

Effective leaders in STEAM education play a pivotal role in the curriculum transformation, and guiding academics and students towards an integrated and holistic approach to science education. Since leadership in STEAM education is essential for fostering innovation and creativity in HEIs, their provision of support, direction, motivation, funding, and engagement with staff, is critical. Furthermore, their role in inspiring and guiding the next generation of thinkers and innovators requires being helpful, encouraging, forward-thinking, professionally developed, and providing academic support.

Leadership should create an enabling and empowering environment for science education, which embraces creativity and undermines bureaucracy. There must be constant and effective communication among all levels involved in curriculum transformation in the system to provide direction, alignment, and commitment. They should generate and sustain interest and motivation in curriculum transformation. Moving from STEM to STEAM requires radical transformation and dealing with resistance to change. Leaders in science education should have leadership competencies in change management in order to achieve curriculum transformation. The shared leadership approaches should be collaborative, inclusive, and empowering to avoid excessive bureaucracy. Curriculum transformation requires creating engaged and diverse teams to sharpen direction and motivate each other. It is critical that this be accompanied by adequate support, funding, clear vision, resources, and accountability. Curricula in science education must be readdressed to assess the extent of transformation that is possible and enact this.

The study was exploratory in nature and drew on qualitative research. The data was generated from one workshop, with a small sample. The study findings cannot thus be generalized beyond the study context, but can be transferred to a similar context. The study does, however, provide insights into diverse perspectives into the role of leadership in curriculum transformation. Future research can thus draw on a mixed methods study with a large and diverse sample across various HEIs to gather multiple perspectives. Further studies should develop evaluative tools for the transformed curriculum and nature of the transformation, and its implications for diverse stakeholders.

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Declaration of Interest

The authors declare no competing interest.

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REIMAGINING PRESCHOOL PEDAGOGY: AI-ENHANCED TEACHING THROUGH MULTILITERACIES-INFORMED CURRICULUM INNOVATION

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Abstract

The integration of Artificial Intelligence (AI) into early childhood education raises important pedagogical questions about how to design inclusive, multimodal learning experiences that nurture children's agency and critical literacies. This paper analyzes sixty AI-enhanced teaching scenarios, developed during a national training program, through the lens of Multiliteracies and Learning by Design (LbD). Using thematic analysis, the study identifies how the four knowledge processes–Experiencing, Conceptualizing, Analyzing, and Applying–are supported or constrained by AI-enhanced multimodal activities. Rather than assessing the teachers' intentions, the study highlights the emergent pedagogical affordances and the potential of the LbD model for crafting flexible, inclusive, and socially embedded learning experiences within the Early Childhood Education (ECE) curriculum. The findings suggest that strong foundations are already in place for responsibly integrating Artificial Intelligence (AI) tools into preschool learning environments, while affirming that a systematic, multimodal, and culturally sensitive approach fosters early critical literacy development.

Keywords: *multiliteracies, learning by design, artificial intelligence, early education*

Introduction

The rapid expansion of digital technologies and their integration into educational settings presents new opportunities and challenges for curriculum design, particularly in Early Childhood Education (ECE) (Lampropoulos & Papadakis, 2025). Among the emerging tools reshaping learning environments, Artificial Intelligence (AI) offers novel pathways for knowledge creation, multimodal representation, and playful inquiry, even among young learners (Anastasiadis et al., 2024; Aravantinos et al.,2024; Uğraş et al., 2024; Katsampoxaki-Hodgetts et al., 2024). Simultaneously, the need to address the linguistic, cultural, and multimodal diversity of young learners has prompted a shift toward pedagogical models such as Multiliteracies (Cope & Kalantzis, 2009, 2020; New London Group, 1996). Learning by Design (LbD), grounded in Multiliteracies theory, offers a reflexive, non-linear framework based on four knowledge processes, i.e., Experiencing, Conceptualizing, Analyzing, and Applying, that supports learner agency,

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creativity, and socio-cultural connection before and after AI (Gee & Zhang, 2024). Early childhood settings, traditionally characterized by playfulness, experiential learning, and creativity, must now navigate the responsible integration of AI without compromising these core attributes. Designing AI-enhanced learning scenarios thus demands careful pedagogical planning that simultaneously nurtures children's agency, multimodal literacies, and cultural awareness (Katsampoxaki-Hodgetts et al., 2024).

As recent scholarships suggest, the infusion of AI into early learning environments offers unique opportunities for children to contribute their lived experiences into collective meaning-making processes, transcending the sum of individual knowledge (Zapata, 2023; Gee, 2024). In this context, young learners are positioned as active co-constructors of knowledge, building bridges between firsthand experiences, emerging digital landscapes, and the broader social world.

AI-integrating scenarios involve a deeper pedagogical embedding of AI, where the design and implementation of the learning experience are consciously shaped by the capabilities, limitations, and socio-cultural implications of AI technologies (Katsampoxaki-Hodgetts et al.,2024; Zawacki-Richter et al., 2019). Here, AI is not merely an add-on but becomes a catalyst for rethinking learning processes, promoting critical inquiry, co-creation, and multimodal meaning-making (Kalantzis & Cope, 2020; Zapata et al., 2023). Understanding this distinction is essential for evaluating how early childhood education curricula can responsibly incorporate AI to foster agency, reflexivity, and culturally sensitive literacies from an early age.

Despite growing interest in integrating AI into early childhood education, there remains a lack of research on how such technologies can be meaningfully embedded within pedagogies that prioritize multimodal, inclusive, and culturally responsive learning. This gap highlights the need for frameworks that support educators in designing AI-enhanced activities that nurture young children's agency and critical literacies.

The aim of this study was to analyze preschool teaching scenarios that incorporate AI, focusing on how they reflect the principles of Multiliteracies Pedagogy and Learning by Design. The study seeks to identify both pedagogical affordances and challenges that arise when AI is integrated into early learning environments.

The research question guiding this study was:

How are the four knowledge processes of Learning by Design manifested in AI-enhanced preschool teaching scenarios, and what pedagogical opportunities arise through the prism of Multiliteracies Pedagogy?

Theoretical Framework

Multiliteracies Pedagogy in Early Childhood Education

The Multiliteracies Pedagogy (MLP), first proposed by the New London Group (1996) and further developed by Cope and Kalantzis (2009, 2020), offers a dynamic, interdisciplinary, and culturally responsive framework for learning and teaching. It positions learners as active meaning-makers navigating diverse linguistic, cultural, and multimodal landscapes. In early childhood education, adopting a Multiliteracies perspective is especially critical, as children's earliest educational experiences shape their developing identities, critical capacities, and creative expression (Gee, 2007).

https://doi.org/10.33225/BalticSTE/2025.104

The MLP framework recognizes four interconnected knowledge processes:

- Experiencing (Engaging with the known and the new)
- Conceptualizing (Developing generalizations, classifications of concepts, properties, principles, and terminology)
- Analyzing (Critically examining and evaluating knowledge)
- Applying (Creatively transferring and transforming knowledge in practice)

In this view, learning is neither linear nor hierarchical but emerges from the recursive interplay of these processes within richly multimodal and socially situated environments. In early childhood settings, this approach invites a shift from traditional teacher-centered instruction toward child-centered, participatory, and culturally inclusive practices that honor diverse ways of knowing and expressing (Kalantzis & Cope, 2020).

In this study, the Multiliteracies Pedagogy framework is complemented by the Learning by Design model, which serves as the analytical tool for interpreting AI-enhanced teaching scenarios (see Research Methodology section).

Artificial Intelligence and Multiliteracies in Early Learning Contexts

The integration of AI into early childhood education is still an emerging area of practice and research (Anastasiades et al., 2025; Lampropoulos & Papadakis, 2025). AI tools, when critically selected and pedagogically framed, can offer powerful opportunities for fostering multimodal literacy, inquiry, collaboration, and creative production among young learners. Story generators, image creators, and conversational AI interfaces can expand children's repertoires of symbolic expression, enabling them to engage with diverse modes such as text, sound, movement, visual art, and interactive media (Zapata et al., 2023).

However, the mere use of AI does not guarantee meaningful learning. Without careful pedagogical framing, AI risks reinforcing passive consumption, superficial engagement, or technological determinism. Therefore, a Multiliteracies and Learning by Design perspective provides a necessary critical lens for ensuring that AI is mobilized to support active, reflexive, and socially situated learning rather than displacing the playfulness, relationality, and embodied experiences that are foundational to early childhood development (Gutierrez, 2009; Wohlwend, 2018). In this study, the intersection of AI, Multiliteracies, and LbD offers a fertile ground for reimagining early childhood curriculum design: one that leverages technological affordances to deepen, rather than dilute, children's agency, critical awareness, and creative literacies.

Research Methodology

Design

This study adopted a qualitative research design, employing thematic analysis (Braun & Clarke, 2006) to analyze how preschool educators' AI-enhanced teaching scenarios embodied the knowledge processes proposed by the Learning by Design (LbD) framework, viewed through the lens of Multiliteracies Pedagogy. The research was conducted in April 2025 and focused on scenarios developed as part of a national professional development program in Greece. The approach was interpretive, grounded

https://doi.org/10.33225/BalticSTE/2025.104

in socio-cultural theory, and aimed to uncover pedagogical patterns within the dataset. Rather than evaluating the educators' original intentions, the analysis focuses on the pedagogical affordances and constraints emergent in the design and description of the scenarios.

Context and Data Collection

The dataset consisted of sixty (60) written teaching scenarios developed by preschool educators who participated in a 400-hour national professional development program focused on the pedagogical use of Artificial Intelligence and digital technologies. Each scenario included a description of learning objectives, a sequence of planned activities, the AI-enhanced digital and non-digital tools employed, and anticipated student actions and responses. The scenarios were submitted as part of the program's final portfolio requirements and were anonymized before analysis.

Analytical Framework

Thematic analysis was guided by the four knowledge processes of the LbD model (Kalantzis & Cope, 2020): Experiencing (personal and new experiences), Conceptualizing (naming concepts and theorizing relationships), Analyzing (functional and critical examination of knowledge), and Applying (appropriate and creative transfer and transformation). Initial coding focused on identifying explicit or implicit references to these processes. Through iterative rounds of analysis, the data were organized into sub-themes reflecting multimodal engagement strategies, uses of AI tools, and the socio-cultural positioning of learning activities.

The analysis unfolded as a continuous and iterative process. It began with familiarization, where repeated readings of the scenarios allowed for a deep understanding of their overall structure, intentions, and pedagogical orientation. Building on this immersion, initial coding was conducted by developing thematic codes directly aligned with the four knowledge processes of the Learning by Design framework. As coding advanced, the emerging themes were further refined into sub-categories, including patterns such as multimodal representations, the use of personal narratives, the presence of critical discussions, and the integration of AI-assisted creativity. Through reflective synthesis, these categories were interpreted not simply as isolated practices but as indicators of broader pedagogical trends and opportunities within the early childhood education context. To support the systematic organization and retrieval of data throughout this process, NVivo 14 software was employed, enabling a more rigorous and transparent analysis of the collected scenarios.

Learning by Design as an Analytical Lens

Learning by Design (LbD) operationalizes the Multiliteracies epistemological framework into a flexible and reflexive model for curriculum design. By emphasizing knowledge as an active, situated, and transformative process, LbD aligns with contemporary visions of early childhood learning that value agency, play, exploration, and the social construction of meaning.

https://doi.org/10.33225/BalticSTE/2025.104

The LbD framework identifies four pedagogical knowledge processes:

- Experiencing the Known and the New: Engaging children's lived experiences and introducing new encounters that challenge or expand understanding.
- Conceptualizing by Naming and Theorizing: Encouraging children to recognize patterns, develop conceptual categories, and articulate emerging understandings.
- Analyzing Functionally and Critically: Supporting children in exploring how things work and why they are the way they are, including social, cultural, and ethical dimensions.
- Applying Appropriately and Creatively: Enabling children to transfer knowledge across contexts and to reframe or redesign meanings in new ways.

In applying LbD to preschool AI-enhanced teaching scenarios, this study examines how digital technologies, particularly AI tools, either activate or inhibit these learning processes, with particular attention to multimodal meaning-making and socio-cultural positioning.

The study adopts a reflective and interpretive orientation rather than a frequency-based or purely descriptive one. Emphasis is placed on understanding how teaching practices position young learners as active participants in meaning-making, critical inquiry, and knowledge transformation, consistent with the socio-cultural commitments of Multiliteracies Pedagogy (Cope & Kalantzis, 2009). By examining not only what activities are planned but also how they engage with multimodality, socio-cultural relevance, and critical thinking, the analysis seeks to surface deeper pedagogical potentials for future early childhood curriculum innovation.

Research Results

The sixty AI-enhanced teaching scenarios are aligned with the four knowledge processes of the Learning by Design (LbD) framework: Experiencing, Conceptualizing, Analyzing, and Applying. Analysis revealed consistent patterns in preschool educators' design of AI-integrated activities, demonstrating both supportive and constraining effects on multimodal and socio-cultural learning processes.

Experiencing: Bridging the Known and the New

The analysis of the Experiencing process revealed two key strands: activities that built on children's prior knowledge ("Experiencing the Known") and those that introduced new concepts or experiences ("Experiencing the New"). Educators designed scenarios that connected personal experiences to new learning through AI tools and multimodal resources, aiming to deepen engagement and understanding.

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Table 1
Experiencing: Bridging the Known and the New in Early Education Teaching Scenarios, integrating AI

Type of Experienced Knowledge	Frequency (Number of References)	Pedagogical Perspective	Indicative Teaching Opportunities	Example from Teaching Scenarios
Experiencing the Known	18	Leveraging children's personal experiences and strengthening emotional connection to knowledge.	Narratives and multimodal practices around diseases and microbes, racism and poverty, brushing teeth and microorganisms, family nutrition, and experiences with water.	The teacher shares a personal story about walks among flowers, inviting children to draw their own memories.
Experiencing the New	20	Creating conditions for inquiry, experimentation, and interpretation of new or unknown concepts.	Exploration of plant-based pesticides, virtual microorganism simulations, virtual experiments, and discussions about scientific and technological developments (e.g., greenhouse in Africa).	Through a story, children wonder what they saw and conduct a salt melting experiment to investigate.

Experiencing emerged as a foundational knowledge process across the majority of scenarios, highlighting the centrality of connecting children's personal experiences with new encounters mediated through AI and multimodal tools (Table 1). In many cases, educators intentionally anchored learning in children's familiar worlds, such as memories of playing with water, encounters with different seasons, or everyday phenomena like tooth brushing and nutrition. For example, children were invited to recount personal memories of encountering ice or steam, before experimenting with phase changes in a guided activity. Simultaneously, scenarios also introduced novel experiences through AI-mediated simulations and storytelling, such as virtual explorations of distant ecosystems or creative engagement with digitally generated narratives. Through "Experiencing the New," children encountered previously unknown concepts like biodiversity, renewable energy, or the water cycle in unfamiliar contexts. Importantly, the integration of AI tools, such as story creators, digital exploration platforms, and visual generation applications, served to augment, rather than replace, embodied and emotional dimensions of experience (Table 2). Yet, the pedagogical effectiveness of these experiences depended on thoughtful framing by educators: when experiences were mediated through guided inquiry, critical reflection, or playful dramatization, children's engagement was notably deeper and more participatory.

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Table 2

Ways of Integrating AI in Early Education Teaching Scenarios

Evaluation Method / Assessment	Example (Qualitative Data)
Video creation (Lumen5)	Children create videos with sound and images about local products.
Worksheet & Self/Peer-assessment	Self-assessment and group evaluation using worksheets.
Interactive digital exercises (LearningApps)	Climate change assessment games using LearningApps.
Comparative Concept Maps	Comparing new and original concept maps about climate change.
Theatrical Play	Theatrical play about marine pollution.
Padlet (photo/audio uploads)	Uploading photos and audio recordings on Padlet.
Collage creation (Seasons)	Creating collages about the seasons.
Reflective questioning ('Then-Now')	Reflective thinking routine 'Then I Thought – Now I Know' about seasons.
Letter Writing	Writing a letter to a character about the seasons.
Drawing Activities	Drawing and depicting the seasons.
ELPEIDA Software	Evaluation via ELPEIDA software (bar charts).
Gamified activities (Educaplay, Wordwall)	Assessment through gamified activities on Educaplay and Wordwall.
Evidence-based reflection (K-W-L-H)	Using K-W-L-H diagram for reflection.
Story creation (StoryJumper)	Creating digital albums with StoryJumper.
Reflective group presentation & discussion	Group presentation and reflective discussion of creations.
Flexible grouping and formative assessment	Flexible grouping and use of K-W-L-H strategies.
MagicSchool AI & Canva	Using MagicSchool AI and Canva for digital board creation.
Quizizz	Online quiz assessment using Quizizz.
Wordwall games	Interactive Wordwall games about volunteering.

https://doi.org/10.33225/BalticSTE/2025.104

Quiz (Quizziz, emotions)	Emotion-focused quiz on Quizziz.
Adobe Spark Video	Video creation about emotions using Adobe Spark.
Observation and Interviews	Observation and interviews for assessment.
Portfolio of Student Work	Collecting student work in portfolios.
Rudolph AI feedback	Feedback from AI (Rudolph AI).
Four Season Box Activity	Four Season Box activity.
Canva Concept Map	Creating digital concept maps with Canva.
Theatrical dramatization & Pixel Art (ELPEIDA)	Theatrical dramatization and Pixel Art creation via ELPEIDA.
Kahoot Quiz	Knowledge quiz with Kahoot.
LearningApps Multiple Choice Games	Multiple choice games using LearningApps.
KWLH Diagram (digital)	Filling digital KWLH diagram.
ChatGPT Questionnaire	Evaluation questionnaire created with ChatGPT.
Parent feedback (blog comments)	Parent feedback through blog comments.
VoiceMod & Fliki AI (colors/emotions)	Expressing emotions through color and sound with VoiceMod and Fliki AI.
Mindmap & Kahoot	Mindmapping and Kahoot evaluation.
NightCafe Image Creation	Image creation using NightCafe.
ChatGPT-created Multiple Choice Questions	Multiple choice questions generated by ChatGPT.

Table 2 presents a variety of AI-enhanced assessment and activity methods designed by preschool educators. The data show that educators integrated a wide range of digital tools, including video creation, interactive quizzes, reflective activities, and multimodal storytelling, demonstrating an emphasis on multimodal engagement and formative assessment.

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Conceptualizing: Building and Structuring Meaning

The Conceptualizing process focused on how children organized and structured knowledge using AI tools. The analysis identified a range of strategies from simple classification tasks to more complex mind mapping and inquiry-based activities.

Table 3

Conceptualizing: Building and Structuring Meaning in early Education Teaching Scenarios integrating AI.

Conceptualization Practice	Frequency	Example from Scenarios
Creating mental maps	21	Children create a mental map recording their views on 'volunteering' using Coggle.
Grouping and classifying objects	18	Children describe characteristics of squares and rectangles and compare them.
Investigating and consolidating concepts	26	Discussion in plenary after viewing a video to elicit children's thoughts.
Comparative analysis and inquiry questions	17	Comparing similarities and differences between squares and rectangles.
Brainstorming and clarification	22	Guiding children to answer an inquiry question collectively.
Using thinking routine questions	14	Using 'See-Think-Wonder' thinking routine.
Connecting new knowledge with prior knowledge	20	Recording newly acquired knowledge in a concept map.

As shown in Table 3, the scenarios demonstrated varied degrees of success in fostering conceptualization, the process through which children organize, name, and theorize knowledge. On the one hand, educators frequently employed strategies such as the creation of mind maps, classification activities (e.g., sorting seasons or geometric shapes), brainstorming sessions, and guided discussions to scaffold conceptual understanding. Digital tools like Coggle, Kidspiration, and Canva were utilized to support the visual organization of ideas, enabling children to construct conceptual relationships multimodally through images, colors, and words. In stronger examples, conceptualization was embedded within inquiry-based approaches: children compared their initial and revised understanding of environmental concepts after engaging with AI-generated videos or simulations.

However, the analysis also revealed that in approximately one-third of the scenarios, conceptualization remained surface-level. In these cases, activities were limited to nominal labeling ("this is evaporation") without encouraging deeper theorization or relational thinking.

Analyzing: Fostering Early Critical Awareness

The Analyzing Knowledge process focused on how children were encouraged to engage in both functional and critical examination of knowledge. The scenarios

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demonstrated varied approaches, including prompting children to explore how AI tools work and fostering early critical literacy through activities that compared human and AI-generated outputs. Although Analyzing is typically considered a challenging process to develop in early childhood education, the analysis highlighted several creative strategies educators used to introduce questioning, verification, and reflection into their lessons.

Table 4

Analyzing: Fostering Early Critical Awareness in Early Education Teaching Scenarios, integrating AI

General Category	Frequency	Indicative Example from teaching scenarios
Critical Analysis	12	Children verify ChatGPT's greetings in different European languages by cross-referencing with books, dictionaries, and Google.
Critical Analysis	9	Children are encouraged to question and not accept what they see uncritically.
Critical Analysis	8	Children compare their self-created travel stories to those generated by AI.
Functional Analysis	11	Children search on ChatGPT without keywords to understand how search inputs affect results.
Functional Analysis	10	Children ask questions to a fictional AI painter and compare painting styles across eras and themes.
Functional Analysis	7	Children compare AI-generated images of a grandmother's life based on different prompts.
Critical Analysis	7	Children create a drawing or short story and compare it with the AI-generated version on the same theme, discussing similarities, differences, and how AI can assist learning.

Some of the most promising examples involved activities where children were encouraged to compare their own creative outputs, such as drawings, narratives, or posters, with those produced by AI tools. In these cases, children discuss similarities, differences, biases, and missing elements, prompting early reflections on how knowledge and representations are constructed. For instance, in one scenario, children created personal stories about the seasons and then compared them with AI-generated versions, discussing questions such as: "Why do the AI stories seem similar? Are they missing some feelings or ideas we included?" Another activity engaged children in evaluating translations produced by AI for cultural appropriateness, encouraging critical thinking about language use. These activities exemplify the Multiliteracies emphasis on critical framing, urging learners not only to absorb information but to interrogate its origins, perspectives, and implications (New London Group, 1996). Moreover, they operationalize Analyzing Critically and Functionally, as children recognize both the technical workings, and the socio-cultural meanings embedded in texts and images (Cope & Kalantzis, 2009). Nevertheless, the integrated analysis revealed that critical analysis practices appeared infrequently (in roughly 20 out of 60 scenarios) and often depended heavily on educator prompts.

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Applying: Creating New Meanings through Multimodal Design

The Applying process captured how children used knowledge creatively and meaningfully across new contexts, often through multimodal design and production. The scenarios featured a variety of activities where children transferred and transformed their understanding by creating stories, engaging in dramatizations, conducting experiments, and developing digital artifacts with the help of AI tools. The analysis showed that educators frequently designed opportunities for children to apply concepts in hands-on, imaginative ways that connected scientific understanding with emotional and social themes, reinforcing the Learning by Design model's emphasis on knowledge transformation.

Table 5

Applying: Creating New Meanings through Multimodal Design in Early Education Teaching Scenarios, Integrating AI

Epistemic Design	Knowledge Process	Frequency (*n* = 60)	Example from teaching scenarios
Story creation for concept familiarization (Storytelling)	Applying the Known	41	We begin with a story about a raindrop traveling the world.
Children's personal narratives/experiences	Applying the Known	28	Children recall where they have seen ice or steam in daily life.
Theatrical play based on content	Applying the Known	33	We transform into raindrops and move like changing water.
Introduction of scientific terms and concepts	Applying the New	49	We introduce the terms 'evaporation,' 'condensation,' through a video.
Viewing and analysis of educational video	Applying the New	52	We watch the droplet's journey video and explain changes through drawings.
Experimentation/Observation of phase change	Applying the New	45	We place ice cubes under the sun and observe what happens.
Reflective questioning with teacher support	Applying the New	19	The teacher asks: 'What would happen if there were no sun?'
Linking with social/emotional themes (e.g., friendship)	Applying the Known	27	The raindrop meets new friends – we discuss feelings about losing a friend.

The knowledge process of Applying was strongly represented across the dataset, affirming the commitment of many educators to foster children's agency in generating new meanings, not merely consuming information. Children engaged in a variety of productive tasks that embodied Applying Appropriately and Creatively, including:

- Designing collaborative storybooks using StoryJumper
- Creating virtual museums of environmental artifacts using Canva and Padlet
- Producing digital posters and short videos expressing scientific or emotional themes

For example, children were invited to produce alternative narratives that combined scientific concepts (e.g., water cycle processes) with emotional and social themes (e.g., making new friends, experiencing loss).

Discussion

The findings of this study affirm that AI integration into early childhood teaching scenarios offers meaningful opportunities for fostering multimodal, inclusive, and critically engaged learning. Consistent with prior research (Anastasiadis et al., 2024; Zapata et al., 2023), the scenarios demonstrated that AI tools were frequently used to enrich experiential learning through storytelling, simulations, and interactive media. These strategies supported children's engagement with both familiar and novel content, echoing Gutiérrez and Rogoff's (2003) emphasis on expanding children's "funds of knowledge" in culturally responsive ways.

Conceptualization practices, as highlighted in the results, showed a range of success. The strong use of digital concept mapping, inquiry-based discussions, and visualizations mirrors findings by Jiménez-Aleixandre and Erduran (2007), who argue that early science education benefits from scaffolding that supports children in making conceptual connections. However, the present study also revealed that some scenarios limited conceptual work to surface-level naming, reaffirming concerns noted by Cope and Kalantzis (2015) that deep learning requires iterative cycles of reflection and theorization.

A notable strength emerged in how educators designed analyzing activities. Although Analyzing is widely regarded as difficult to foster in early childhood settings (Luke, 2018), many scenarios succeeded in inviting children to critically evaluate AI outputs, compare their own creations with those of AI, and question digital representations. These practices align with the Multiliteracies framework's call for critical framing (New London Group, 1996) and reflect emerging scholarship (Gee & Zhang, 2024) emphasizing that young learners can develop early critical literacies when properly scaffolded. Nevertheless, as Wohlwend (2018) also cautions, the integration of critical discussions must become routine rather than exceptional; otherwise, critical thinking remains peripheral.

In the Applying process, the study found compelling examples where AI was positioned as a creative partner rather than a passive tool. Children's multimodal productions—whether digital stories, dramatic reenactments, or creative artworks—illustrated the potential of AI to enhance expressive and socio-emotional learning. This supports Wohlwend's (2018) vision of young learners as "designers of social futures." However, the data also suggested a risk: without sufficient pedagogical framing, there is a danger that AI-supported creation may become ornamental rather than transformative, a concern echoed by Gutiérrez (2008) in her critique of surface-level digital engagement.

One persistent challenge across the dataset was the need for deeper integration of critical literacy around AI itself. While many scenarios utilized AI to augment learning, fewer addressed the ethical, social, or cultural implications of AI use. This gap points to the necessity of extending beyond functional digital literacy towards what Gee (2024) describes as "cybersapien literacy," which involves understanding AI as both a technical tool and a socio-cultural actor.

Many scenarios reflected an understanding that application is not about mechanical reproduction but about re-designing meaning in novel contexts (Kalantzis & Cope, 2020). In the strongest cases, AI tools were positioned not as authoritative sources but as creative partners, with children critically evaluating and modifying AI-generated outputs to better express their intended meanings.

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In sum, the study's findings are largely congruent with existing literature but also highlight key areas for pedagogical development: scaffolding deeper conceptual engagement, embedding critical reflection systematically, and leveraging AI not only for technical enhancement but also for socio-cultural and ethical inquiry. Future research should continue exploring these dimensions, potentially integrating broader theoretical lenses such as posthumanist perspectives (Zawacki-Richter et al., 2019) to further interrogate AI's role in early learning environments.

Limitations and Implications for Practice and Further Research

While this study provides valuable insights into the pedagogical dynamics of AI use in early childhood education, certain limitations must be acknowledged. The analysis focused on written teaching scenarios rather than observed classroom practices, which limits insights into real-world enactment. Additionally, while educators were well-trained, their AI integration practices remain emergent. To strengthen these outcomes, professional development should focus on equipping educators with strategies for embedding critical digital literacy and ethical inquiry into AI-enhanced activities. Finally, the study reflects a national context, which may affect its broader applicability.
Future research should explore the enactment of such scenarios in real classroom settings and consider cross-cultural comparisons. Table 6 summarizes the observed potential and offers practical recommendations for further research and development. Moving forward, professional development initiatives should emphasize scaffolded critical engagement with AI and encourage culturally and ethically aware applications. Moreover, activities that compare children's own creations with AI-generated outputs should be enhanced with scaffolded reflective questioning to deepen metacognitive thinking and self-regulation. Educators could also design narrative scenarios that introduce ethical dilemmas, prompting children to reflect critically on AI's possibilities and limitations, thereby developing their technological literacy. Additionally, expanding the use of AI-supported tools to create digital portfolios or emotional diaries would allow children to integrate personal narratives and foster identity-building, while integrating intercultural and community-focused storytelling projects can promote social inclusion and cultural sensitivity, ensuring that learning is both locally meaningful and globally aware. Finally, systematic analysis of AI-generated outputs for potential biases, such as those related to gender, culture, or age, should be embedded in learning activities to raise children's critical awareness of representation and diversity in digital contexts.

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Table 6
Observed Potential of AI-integrating Teaching Scenarios in Early Education and Opportunities for Further Development

Observed Potential	Pedagogical Benefit	Opportunities for Further Development
Comparison of children's creations with AI outputs	Enhancement of metacognitive thinking and self-regulation	Design activities with scaffolded reflective questioning on AI-human comparison
Reflection on AI's possibilities and limitations	Development of critical technological literacy	Introducing narrative scenarios involving ethical dilemmas using AI outputs
Integration of emotional and personal narratives	Support of identity building and emotional meaning-making	Create digital portfolios or emotional diaries using AI-supported tools
Inclusion of intercultural and diverse cultural references	Promotion of social inclusion and cultural sensitivity	Produce community-focused or culturally themed storytelling projects
Avoidance of stereotypical representations in AI outputs	Raising awareness of diversity and critical reflection on representations	Systematically analyze AI-generated outputs for biases in gender, culture, or age representations

Conclusions and Implications

This study analyzed sixty AI-integrated teaching scenarios designed by preschool educators within a national professional development program, using a Multiliteracies and Learning by Design framework to interpret their pedagogical affordances. The findings showed that AI tools effectively supported experiential and conceptual learning, enabled creative multimodal outputs, and, in some cases, fostered early critical awareness. While many scenarios demonstrated innovative practices, particularly in experiential and creative domains, the analysis highlighted a need for deeper critical framing and conceptual scaffolding to fully realize AI's pedagogical potential in early childhood settings. It is apparent in this study that integrating Artificial Intelligence into early childhood education is not merely a technological decision, but a pedagogical one. AI integration in early education can enrich learning when it is pedagogically purposeful, culturally responsive, and critically reflective. By anchoring AI practices within Multiliteracies and Learning by Design frameworks, educators can create inclusive, critical, and culturally responsive learning environments from the earliest years. Future research and professional development must continue to center young learners' agency, imagination, and ethical engagement as we design early curricula for an AI-mediated world.

Declaration of Interest

The authors declare no competing interest.

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METACOGNITIVE STRATEGIES FOR READING SCIENTIFIC AND SUSTAINABILITY-RELATED CONTENT IN DIGITAL AND PRINT MEDIA

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Abstract

The reading medium - digital or print – Impacts university students' use of metacognitive strategies when engaging with sustainability- and science-themed content. The research aims to identify commonly applied strategies and examine how the medium affects their application and comprehension of environmental topics. Seventy students participated in the study, divided into two groups based on their reading medium. Data collection included the Metacognitive Reading Strategies Questionnaire (MRSQ) and a comprehension test focused on sustainability-themed content that incorporated scientific elements, followed by qualitative group discussions. Results indicate that print media foster deeper understanding through reflective strategies, while digital media support selective and rapid reading, providing broader contextual insights but often resulting in more superficial comprehension. These findings highlight the need to adapt curricula to incorporate both sustainability and scientific content in diverse media formats, fostering critical thinking, metacognitive awareness, and both environmental and science literacy. The study emphasizes the role of such adaptations in equipping students with the skills necessary to interpret scientific information, address environmental challenges, and promote sustainable development.

Keywords: *metacognitive strategies, reading comprehension, reading media, science literacy, sustainable content*

Introduction

Over the last decade, digitalization has transformed how we access information while raising concerns about its impact on understanding and perception. This is especially relevant as sustainability- and science-related texts demand reflection and source evaluation. Sustainability and science often overlap, especially in fields like environmental science and climate change, requiring critical interpretation. This study addresses the relationship between reading media, specifically online and print reading, and the use of metacognitive strategies in understanding such content, emphasizing that the reading process in educational contexts should go beyond acquiring information; it should involve critical thinking, reflection, and evaluation of information credibility – all of which may be shaped by the reading medium.

Although the study focuses on Slovenian university students, its findings have broader relevance for international higher education, especially amid global shifts toward

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digital learning and increased emphasis on sustainability and science literacy. While it does not propose a novel theoretical or methodological framework, it contributes by applying established models – Bloom's revised taxonomy and the Metacognitive Reading Strategies Questionnaire – to a timely and underexplored context. It explores how university students engage metacognitively with sustainability- and science-related content across digital and print media. These findings provide practical insights for fostering critical thinking, metacognitive awareness, and adaptive reading strategies, informing curriculum design aligned with the demands of 21st century learning.

The next section defines key concepts related to metacognitive reading strategies in science and sustainability contexts, followed by the research aim and questions. The methodology outlines the design, instruments, and analytical procedures. Results detail strategy use and comprehension outcomes across reading formats. The discussion interprets the findings and suggests practical implications. The paper concludes with relevance for education and directions for future research.

The Importance of Metacognitive Strategies in Reading

Metacognition is one of the processes that can help us learn about the process of being aware of and in control of one's own thoughts (Drigas & Mitsea, 2021; Flavell, 1976). It encompasses not only awareness but also the regulation of cognitive processes, including deep knowledge, planning, self-monitoring, and adaptation (Drigas & Mitsea, 2021), which improve the quality of learning by allowing the learner to monitor, regulate and organize his or her cognitive processes (Rivas et al., 2022), positioning metacognition as a key component of effective and autonomous learning. It also facilitates the transfer of self-regulation skills to different learning domains. Learners who use metacognitive strategies tend to be more successful in online learning and self-regulation (Anthonysamy et al., 2020). Their reading comprehension and overall reading ability are also improved, which indirectly leads to better academic achievement (Köse & Güneş, 2021; Mihud et al., 2020). Typical metacognitive reading strategies include note-taking while reading, highlighting important information, focusing on key details, reviewing text content, formulating questions, making predictions, and engaging in self-regulatory practices (Drigas & Mitsea, 2021). Such strategies are particularly recommended for reading digital texts, where distraction and nonlinearity are common (Kimova et al., 2024). To enhance learning outcomes, it is essential to integrate metacognitive strategy instruction into educational programs. This enables learners to plan, monitor, and adapt their strategies according to task demands (Wing Han Chan et al., 2021), thereby fostering critical thinking, self-regulated learning, and decision-making, even in complex learning environments (Pandey & Mohan, 2024).

Sustainability Themes and Critical Thinking

Critical thinking is essential for tackling global issues (Fandiño Parra et al., 2021) and is closely linked to understanding sustainability topics, which are one of the key elements of learning in the 21st century classroom (Wing Han Chan et al., 2021). Sustainability education empowers learners as active agents of change (Jónsson et al., 2020) and is relevant at all levels of education (Zwickle & Jones, 2018). Davies (2015)

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emphasizes that sustainability and critical thinking should be treated as distinct yet complementary skills. Sustainability texts often include scientific explanations, data, and causal reasoning – central to science literacy. Metacognitive awareness supports deeper understanding of both environmental and scientific content, fostering informed and reflective engagement with global challenges.

Differences Between Reading Digital and Printed Texts

Metacognitive reading strategies should be more systematically embedded in university education, as students often make limited use of them (Anthonysamy et al., 2020), and reading comprehension is reportedly declining (Ribeiro et al., 2019). Reading is shaped by the medium (Habok et al., 2024; Oshima, 2024), and digital environments pose specific challenges. Strategies such as note taking, identifying key information, reviewing content, posing questions, making predictions, sustaining attention, and engaging in self-regulation play a crucial role in digital environments (Klimova et al., 2024). Digital texts, especially longer and more complex ones, are often perceived as more difficult to follow (Baron, 2021), which may explain readers' preference for print in depth reading (Spencer, 2006). However, digital texts also offer unique affordances, such as hyperlinking and multimedia integration, which provide ways to engage with information and support reading flexibility, which is also noticed by Furenes et al. (2021). These differences matter especially when reading science-based and sustainability texts, which require both surface-level scanning and deeper reflection. Understanding how each medium shapes strategy use is key to developing effective educational practices.

Research Aim and Questions

Although many studies address specifics of online reading, little attention has been given to how different reading media affect the use of metacognitive strategies when engaging with sustainability- and science-related content. Such texts require not only comprehension but also critical evaluation, integration of prior knowledge, and higher-order thinking. Prior research highlights the role of metacognition in learning and addressing sustainability challenges (Bohm, 2024). Deep learning supports meaning-making in complex domains like sustainability education (Warburton, 2003), which often relies on scientific reasoning and data interpretation.

This study, therefore, explored how university students' use of reading media affects their use of metacognitive reading strategies when engaging with sustainability-related content that requires critical thinking and source evaluation skills. The purpose of the study was to identify which strategies are most commonly used and to determine how different reading media affect students' ability to understand and engage with scientific and sustainability-oriented content. By doing so, the study aims to inform educational practices that promote deeper comprehension and critical engagement with complex informational texts across formats.

The research was guided by two research questions: (1) How do university students use metacognitive strategies when reading about sustainability- and science-infused content, and which strategies are most common? (2) How do different types of texts (digital or print) affect their use of metacognitive strategies and their understanding of sustainability and science-related topics?

https://doi.org/10.33225/BalticSTE/2025.120

Research Methodology

General Background

Understanding how reading medium affects the activation and use of metacognitive strategies is particularly important when students encounter cognitively demanding texts – such as those related to sustainability and science – that require data interpretation, causal reasoning, and critical reflection. Prior research highlights the importance of self-regulation and resource management in digital reading contexts (Zheng & Kim, 2025). Eye-tracking studies further suggest that print and digital formats activate different cognitive processes: printed texts foster focused rereading, while digital texts are often associated with scanning (Jian, 2022). Students themselves tend to associate print with deeper engagement and comprehension – especially in academic contexts (Hargreaves et al., 2022).

Conducted in October 2024, the research employed a quantitative, between-subjects experimental design to compare students' use of metacognitive strategies and comprehension outcomes across reading formats. The theoretical grounding combines Flavell's metacognitive theory (1979), which frames reading as a self-regulated, strategic process, with Bloom's revised taxonomy (Anderson & Krathwohl, 2001), used to assess comprehension depth. The study was carried out at a single Slovenian university, providing controlled conditions while limiting broader generalizability.

Participants

The study involved 70 fourth-year undergraduate students from a teacher education program at a Slovenian faculty of education. All participants were enrolled in a didactics course focused on mother tongue instruction, where reading strategies and media are regularly discussed. The average age of the participants was 22.4 years. The sample included 67 female and 3 male students; however, due to the low number of male participants, no gender-based comparisons were conducted.

Participants were recruited from the same course group, with no exclusion criteria applied. The activity was part of regular coursework, the participation in the study was voluntary, and all the students present agreed to participate. They received written information about the research aims and gave informed consent, and they were assured of their right to withdraw at any time without penalty.

To enable comparative analysis, students were randomly assigned to two equally sized groups: one read a printed version of the text, and the other used personal digital devices to access the same content. The sample size was determined by course availability and the need for balanced groups with sufficient statistical power.

Instrument and Analytical Methods

For the purpose of this study, two measurement instruments were used: the Metacognitive Reading Strategies Questionnaire (MRSQ), based on Taraban (2004), and a custom-designed reading comprehension test.

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Since sustainability topics are often not formally included in university curricula in Slovenia, students tend to encounter such content through non-academic sources (Kerneža & Zemljak, 2024), particularly in the form of reading current articles on news websites. Therefore, the most up-to-date article on the most read Slovenian news portal (as reported by MOSS) was selected as the primary reading material. Students in the digital group read the article on their smart devices, while the other group received a printed copy of the identical text.

Participants rated their reading strategies on the MRSQ questionnaire in the form of a 5-point Likert scale (1 – never, 5 – always), which allowed for a quantitative measurement of the frequency of use of the strategies. The questionnaire demonstrates high validity and internal reliability, and meaningful interpretability (Taraban, 2004).

To assess reading comprehension, a researcher-developed test was constructed based on Bloom's revised taxonomy (Anderson & Krathwohl, 2001). The test included six open-ended questions, each corresponding to one of Bloom's cognitive levels: knowledge, comprehension, application, analysis, synthesis, and evaluation. The questions were designed to measure how well students understood, interpreted, applied, and critically evaluated the content of the text. Responses were scored on a 3-point scale (1 – incorrect answer, 2 – partially correct, 3 – fully correct), with a maximum score of 18 points.

The test was reviewed and validated by three pedagogical experts, who evaluated the alignment between the questions and Bloom's taxonomy, refined the wording of items, and established strong criteria. A pilot test was conducted on a small sample of comparable students (n = 7). While the items targeted different skills and therefore did not form a homogeneous scale, internal consistency was assessed using Cronbach's alpha as a general indicator of scoring coherence. The result was 0.871, suggesting high consistency in how the items were interpreted and rated. However, this value should be interpreted with caution given the heterogeneity of the items.

Data Analysis

The data from the MRSQ and the reading comprehension test were analyzed using SPSS (version 27). The separate one-way analyses of variance (ANOVA) were conducted. The first ANOVA compared the frequency of metacognitive strategy use between the two reading media (digital vs. print). The second ANOVA explored differences in reading comprehension outcomes across six cognitive levels based on Bloom's revised taxonomy. Mean scores and standard deviations were calculated for each questionnaire item and comprehension test level. Group means were then compared to determine whether there were statistically significant differences between the two reading formats. Statistical significance was set at $p < .05$.

Research Results

After students read the text, the first step of the survey, the MRSQ questionnaire, was used to compare the use of reading strategies between reading online and reading printed texts. The aim was to determine whether the reading medium affected the frequency and type of metacognitive strategies used during engagement with sustainability- and

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science-related content. The results shown in Table 1 illustrate how the reading format affected the use of various metacognitive strategies.

Table 1

Comparison of Reading Strategy Use Across Online and Printed Texts

Reading medium	Online		Printed	
Reading strategy	***M***	***SD***	***M***	***SD***
While reading, I evaluate the text to see if it contributes to my knowledge/understanding of the topic.	3.4	.69	3.3	.82
After reading a text, I predict how I will apply the knowledge I gained from reading.	3.4	.76	3.1	.81
I try to connect prior knowledge about the topic to better understand what I am reading.	4.1	.71	3.9	.71
While reading, I rethink and adjust my prior knowledge about the topic based on the text's content.	3.3	1.00	3.2	.71
While reading, I rethink and adjust my initial questions about the topic based on the text's content.	3.1	.81	2.9	.85
After reading a text, I reflect on the content of the text	3.6	.77	3.2	.96
While reading, I distinguish between information I already know and new information.	3.9	.78	3.6	.60
When information critical to understanding the text is not directly stated, I try to infer it.	3.5	.77	3.1	.74
I look for information that is important to my reading goals.	3.9	.74	3.8	.76
I predict information that will be presented later in the text.	3.1	.97	3.2	.71
While reading, I try to determine the meaning of unfamiliar words essential for understanding the text.	3.8	.63	3.4	1.07
I predict information that will be presented later in the text.	3.3	.82	3.2	.90
While reading, I use my personal strengths to better understand the text.	3.6	.77	3.2	.76
While reading, I visualize descriptions to better comprehend the text.	3.9	.88	3.5	1.02
I notice how difficult or easy the text is to read.	3.7	1.15	3.6	.68
When reading, I take notes to remember the information.	2.5	.90	2.4	1.02
While reading, I underline and highlight important information to easily locate it later.	3.4	1.17	3.0	1.29
While reading, I write questions and comments in the margins to better understand the text.	2.1	1.13	2.3	1.16
While reading, I underline to remember the information.	3.4	1.02	2.9	1.31
I read the material multiple times to retain the information.	4.0	.67	3.8	.69
When I have trouble understanding the text, I read it again.	4.3	.73	4.1	.62

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The analysis of variance (ANOVA) revealed a statistically significant effect of reading format (F = 10.19, p = .001) and of the type of reading strategy (F = 9.92, p = .001). Although the differences between the media were relatively small, their consistency indicates that the text format affected how students engaged with complex informational content.

Overall, the use of metacognitive strategies was overall slightly more frequent in the digital reading group, suggesting that students who read digitally were more likely to use certain strategies. This tendency was particularly evident in strategies aimed at comprehension and navigation of complex or unfamiliar content. In contrast, students who read printed texts more frequently used strategies oriented towards long-term retention and structured organization of knowledge, such as underlining, rereading, and highlighting.

These findings suggest that print media encouraged more deliberate and reflective reading, supporting the structuring of deeper understanding. On the other hand, digital texts prompted a more flexible and adaptive approach, aligned with fast information retrieval and focused decoding. Such differences in strategy use are particularly relevant in the context of reading science-based and sustainability-oriented texts, which require both surface-level navigation and deeper conceptual understanding.

An additional analysis of variance (ANOVA) was conducted to compare reading comprehension scores across six cognitive levels based on Bloom's revised taxonomy, allowing mean scores to be compared between the two reading groups.

Table 2

Comparison of Reading Comprehension Test Results Across Online and Printed Texts

Reading comprehension level	*M* (Online)	*M* (Print)	*Mean difference*	*p*
Knowledge: Recall of basic facts, concepts, or information	3.00	3.00	.00	1.000
Comprehension: Explanation and interpretation of the meaning of information	2.85	2.94	.09	.090
Application: Applying acquired knowledge to new situations	2.50	2.88	.38	.040
Analysis: Breaking down information into components, identifying patterns, and relationships	2.88	2.97	.09	.200
Synthesis: Combining elements to form a new whole or original solution	2.88	2.94	.06	.330
Evaluation: Judging the value of information or solutions based on specific criteria	2.44	2.85	.41	.030

As shown in Table 2, the two groups performed equally at the knowledge level (M = 3.00, p = 1.000). Differences in comprehension, synthesis, and analysis were small and not statistically significant. However, more pronounced and statistically significant differences emerged at the higher cognitive levels of application (p = .040) and evaluation (p = .030), with students in the print group outperforming those in the digital group.

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For the application level, the effect size was medium (Cohen's $d = 0.47$; $\eta^2 = .188$), showing a clear advantage for print readers in applying knowledge. Similarly, at the evaluation level, the effect size was also medium (Cohen's $d = 0.51$; $\eta^2 = .213$), suggesting that print readers demonstrated greater capacity to critically assess the value and implications of the text content.

A deeper analysis of student responses revealed that printed texts encouraged more elaborate thinking, particularly in questions that involved judgment, conceptual transfer, or synthesis. It should also be noted that students who read printed texts generally took more time to read, which may have contributed to the increased depth of their understanding.

Taken together, these findings suggest that print media provided more effective support for cognitively demanding tasks – particularly application and evaluation – while online reading was more suitable for quicker information retrieval, scanning, and synthesis. The distinction is especially relevant when students are working with texts that include scientific data, sustainability scenarios, or complex cause-effect relationships, where deeper engagement and critical interpretation are essential.

Discussion

The study shows that university students use a wide range of metacognitive strategies when reading complex informational texts related to sustainability and science, which helps them to monitor and adapt their thought processes. This supports earlier findings by Drigas and Mitsea (2021) and Flavell (1976), who highlight the importance of metacognition in planning, monitoring, and regulating cognitive activities in response to textual demands. The finding emphasizes that strategy use depends on the reading goals and text requirements, and in the research conducted, they relied on strategies that helped them to understand and master sustainability content.

Strategies related to understanding difficulties with the text, such as rereading in case of comprehension problems and integrating prior knowledge to improve comprehension, were used most frequently, while strategies of an organizational nature, such as writing down questions and comments in the margin, were used least frequently. While the findings are not in line with those of Anthonysamy et al. (2021), who reported a limited use of metacognitive strategies in reading, participants in the present study demonstrated their application, indicating that there is still room for more systematic instruction and reinforcement of metacognitive strategies, especially as we are talking about adult readers who are also confronted with complex topics such as scientific arguments and sustainability issues.

The type of reading medium affects the use of strategies when reading about sustainability topics, with differences in the choice of strategies depending on the reading medium. In the research conducted, print texts promoted in-depth comprehension to a greater extent, while digital texts enabled selective and rapid reading by searching for key information and skimming through the text. These tendencies reflect the nature of scientific and sustainability content, which often includes abstract concepts, cause-effect reasoning, and data interpretation – all of which benefit from different cognitive approaches. This is consistent with research by Habok and Magyar (2024) and Klimova et al. (2024), who confirmed that digital texts support fast, selective processing, which is essential for effective e-reading strategies.

https://doi.org/10.33225/BalticSTE/2025.120

Although digital texts offer a broader contextual insight due to the possibility of linking to additional sources, comprehension was often more superficial. During the informal discussion after completing the questionnaire, students who read print texts appeared to demonstrate a deeper understanding of the content, which is supported by the questionnaire results indicating that they used deliberate metacognitive strategies with print texts. This also supports the findings of Baron (2021), who argues that readers often prefer print texts for cognitively demanding content. Such content frequently includes scientific explanations, conceptual models, or data-driven arguments that require more reflective engagement.

Nevertheless, digital texts enable specific metacognitive strategies that are crucial for selective information retrieval and fast access to resources, which is particularly important in modern information environments where users are confronted with large amounts of information, but at the same time, as Lu and Xie (2023) argue, digital tools enable fast and skillful navigation between information, which supports key information retrieval strategies. These affordances of digital media provide opportunities to develop critical thinking, adaptability, and strategic flexibility – skills that are highly valuable for engaging with sustainability content in a digital age.

Rather than treating science literacy as a separate element, the study shows that scientific reasoning is deeply embedded in how sustainability is communicated and understood. Metacognitive strategies therefore play a dual role: they help students comprehend complex environmental issues and also support the interpretation of scientific data, models, or explanations included in such texts. This dual impact was especially evident among students in the print group, where higher performance was observed in tasks requiring application and evaluation – skills that are central to both scientific reasoning and sustainability-oriented decision making.

Although the research was conducted within a specific national and institutional context, the patterns identified in students' strategy use and comprehension across reading media reflect broader educational dynamics. These insights are valuable for other higher education systems aiming to enhance students' science and sustainability literacy in the digital age.

The findings thus emphasize the need for educational practices that promote metacognitive awareness across different reading contexts. Strengthening metacognitive reading strategies can enhance science literacy and prepare students for the cognitive demands of interpreting scientific issues in a real-world context. Digital and printed texts offer complementary advantages, with digital texts providing faster access to information and printed texts providing deeper understanding. This research directly supports curricular innovation through the integration of both sustainability and digital content.

The findings of the research highlight the need to promote the appropriate use of metacognitive strategies when reading about sustainability topics in digital and print media, with implications for both science and sustainability education. This links with the research of Xie et al. (2023), who confirmed that metacognitive strategies when reading science texts have an impact on science literacy. Such strategic reading contributes to both sustainability awareness and the digital empowerment of learners, strengthening their competencies for informed decision-making and promoting sustainable lifestyles.

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Among the major limitations of the study is the singular insight into the situation within a specific population, which limits generalization to the general population. The study also did not involve long-term observations or in-depth qualitative practices. Future research should include a more diverse sample of learners, including primary and secondary school students, and explore how specific technologies – such as interactive platforms, annotation tools, or artificial intelligence – can support or potentially hinder the development of metacognitive strategies when engaging with science-rich sustainability content.

Conclusions and Implications

The research highlights the key role of metacognitive strategies in university students' reading of sustainability- and science-related content across different reading media. The results show that the students adapt their strategic behavior based on the format of the text, with each medium supporting different cognitive processes. Digital reading allows for quick information retrieval and supports selective, goal-directed strategies, while print reading fosters deeper comprehension, structured reflection, and critical thinking. These findings underscore the importance of teaching students how to navigate and regulate their understanding when faced with complex informational texts that require both environmental and scientific literacy. The ability to apply and evaluate content – skills associated with higher-order thinking – was more pronounced among students who read printed texts, suggesting that reflective metacognitive strategies are especially important for mastering cognitively demanding material.

By promoting metacognitive awareness and flexibility in strategy use, educators can help students develop the competencies needed to interpret scientific data, engage with sustainability discourse, and make informed, responsible decisions in a global context. The integration of both digital and print formats in educational settings should be intentional and purpose-driven, aligned with the reading task and desired learning outcomes.

Ultimately, strengthening metacognitive reading strategies prepares students not only for academic success but also for the critical interpretation of scientific and sustainability challenges that define contemporary society. In doing so, they become not only better learners but also more empowered and responsible global citizens.

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PRE-SERVICE PRESCHOOL AND PRIMARY SCHOOL TEACHERS' ATTITUDES ON ARTIFICIAL INTELLIGENCE: READINESS TO USE AND POTENTIAL CHALLENGES

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Abstract

The use of AI in the training of pre-service preschool and primary school teachers is a significant, but not sufficiently researched, issue. Although the application of AI in education is widely studied, specific studies related to preschool and primary education teacher preparation are rarer. The cognitive, emotional, and motor abilities of children up to 10-12 years require a special approach, so the integration of AI must be careful and methodologically sound.
The research aimed to analyse the readiness of pre-service preschool and primary school teachers to use artificial intelligence (AI) technologies in the educational process and to name the challenges they see. The research is based on qualitative methodology, and the nature of the research is informative-descriptive; interpretive/quantitative content analysis is applied. The data was collected in spring 2024 from 112 university students, using open-ended questions. The analysis revealed that 57.7 % of respondents feel insufficiently prepared to use AI, mainly due to lack of knowledge, practical skills, and technological mistrust. A third of the respondents show motivation to improve in this area, although real experience with AI is often limited to superficial use. In addition, a critical or cautious attitude toward AI emerged, regarding the concerns about the reliability, ethical implications, and the quality of learning. Challenges include educational (decreasing creativity and motivation), social and ethical (lack of communication, addiction), informational (inaccuracy, plagiarism), and technological aspects. Research results show the need to integrate the systematic development of AI competences into educational field studies, to strengthen the ethical and critical approach, and to create practical support measures to achieve a responsible and purposeful AI integration into both the study process and education in general.
Keywords: *artificial intelligence (AI), informative-descriptive study, pre-service preschool teachers, pre-service primary school teachers, qualitative research*

Introduction

It is obvious that artificial intelligence (AI) is changing teaching/learning processes, so it is necessary to understand whether pre-service teachers are ready to integrate AI into educational practice. Improving professional development and teaching practice becomes extremely important. AI tools enable beginning teachers to engage in self-directed professional development by reflecting on their own learning, exploring innovative methodologies, and using a wide variety of resources. This promotes continuous pedagogical development and the ability to adapt to the latest technologies based on AI (Kohnke et al., 2025). Tomaskinova and Tomask (2024) suggest that tailor-

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made workshops, continuing education, peer support, and ethical training are needed to enable teachers to effectively use artificial intelligence tools.

Research shows (Aljemely, 2024) that many teachers do not have enough technical knowledge and digital skills to understand and effectively use artificial intelligence tools, which makes it difficult to apply them in teaching practice. It goes without saying that effective artificial intelligence teaching programmes must be adapted to different subjects. Integration is hindered by the lack of personalised continuous training that includes both technical and ethical aspects (Arranz García et al., 2025).

Research on the pre-service teachers' position towards artificial intelligence (AI) is of particular importance as it allows us to identify their readiness, needs, and attitudes as regards this technology. This technology should become the basis for improving university study programmes, to ensure that teachers acquire sufficient artificial intelligence literacy and are able to effectively integrate it into the educational process.

Empirical studies reveal diverse pre-service teachers' attitude toward AI. For example, Bae et al. (2024)'s study, examining preschool education teachers' attitude towards generative artificial intelligence (GenAI) tools, showed that although some students were familiar with ChatGPT, only a small number of them intended to actively use this technology in their practice. Researchers related this to lingering uncertainty, which manifested itself in emotional responses, such as anxiety and worry (Bae et al., 2024).

Other studies confirm that students' opinions about AI benefits in education are ambivalent, ambiguous (Ice et al., 2008). Karataş and Yüce (2024) found that students positively evaluate AI's potential to personalise learning and improve learning quality. However, at the same time, they expressed clear concerns about potential threats to academic integrity and information reliability. Research also shows that students perceive AI-related feedback as requiring greater engagement but also acknowledge challenges that reflect ambiguous positions on the use of AI (Westmacott, 2017). These conflicting estimates reflect the complex perception of AI.

In recent years, the use of artificial intelligence (AI)- based teaching tools and educational platforms has significantly increased in educational institutions. It is especially important to study how these technologies are assimilated by pre-service preschool and primary education teachers, as their attitude and competencies will directly affect younger students' learning processes and achievements.

Empirical studies reveal that although students recognise the potential of AI in the education process, their opinions often express a balanced position. Many pre-service teachers emphasise that technologies should be seen as an educational tool, not as an educational element in itself.

A significant problem is that, although the number of studies on the application of AI in education is growing, specific work focusing on pre-service preschool and primary education teachers' attitudes is still underrepresented in scientific literature. This lack of research limits the possibility of fully understanding how the most important competencies of teachers are formed in the field of artificial technology application.

Thus, this study aimed to find out how pre-service preschool and primary education teachers feel prepared to use AI technologies for education in the future, and what possible/probable challenges they see.

https://doi.org/10.33225/BalticSTE/2025.133

Research methodology

Design

A qualitative, informative-descriptive study was conducted. The study applied interpretive content analysis. It was appreciated that interpretive content analysis is a flexible method that does not limit itself to only visual content calculation. Such a technique involves coding text segments into subcategories and categories, focusing on hidden meanings and context (Drisko & Maschi, 2015). Analysing texts in the context of their use, content analysis differs from other research methods and is a highly productive research technique (Krippendorf, 2004). It is assumed that content analysis allows for the objective and systematic identification of specific characteristics of selected objects (Gao, 2009). This is part of a complex study, the quantitative analysis results of which were published earlier (Lamanauskas & Makarskaitė-Petkevičienė, 2025a). The study was conducted in March-April 2024 (during the spring semester).

Sample

The research sample consisted of university students in their first to fourth year of study, pre-service preschool and primary education teachers. All respondents were women. In this regard, possible differences between variables by gender are not analysed. A total of 112 Vilnius University students participated in the study, but the sample consisted of two structural divisions of the institution – the main division and the stem division, located in the northern region of Lithuania.

The study used a non-random, convenient sample. This sampling strategy was used because the population is relatively small, the study focuses only on university students of a defined profile, and the population itself is quite homogeneous. The researchers assessed the methodological point that if researchers carefully conduct the research using a convenience sampling technique and controlling biases and uncertainty, it produces useful data (Golzar et al., 2022). In addition, it can be especially useful for performing qualitative research, when detailed, nuanced data are desired. Convenience sampling, as a non-probability sampling, is quite often used in qualitative research and is a really popular sampling method (Hultsch et al., 2002; Zhao, 2020).

Instrument

The research applied open-ended questions. In the written survey, everybody was given the same questions. The researchers argue that this is useful because it aims to gain a deeper understanding of the respondents' opinions or to assess specific aspects. A series of open-ended questions were asked. This analysis presents the results based on two open-ended questions:

- Do you feel adequately prepared to use artificial intelligence technologies in your future teaching career?
- What potential challenges or shortcomings do you see in using AI in education?

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In the two questions presented in the study, students were asked to describe and comment on their readiness to use AI technologies and possible (expected) challenges. These questions are a component of a complex research instrument (Lamanauskas & Makarskaitė-Petkevičienė, 2025a, 2025b). Some of the research results have been published previously according to other research aspects (Lamanauskas, 2024; 2025b).

Data analysis

A quantitative content analysis of the collected verbal data was performed using basic descriptive statistics. Absolute and relative frequencies were calculated and expressed as percentages. According to Taherdoost (2020), descriptive data analysis is recognized as the first type of data analysis.

Multiple readings of the extracted text array were performed. Meaningful units were identified – text segments that contain meaningful information. Several similar meaning units were combined into larger groups (subcategories). Later, semantically close subcategories were grouped into categories. This makes it possible to create a semantic structure that allows a clearer understanding of the phenomenon under study. The studied content categories were later evaluated quantitatively (George, 1959; Neuendorf, 2002). According to Shapiro and Markoff (1997), content analysis primarily means any systematic reduction of textual data to a standard and, at some level, statistically processed set of symbols.

Research Results

The respondents' position on the benefits of AI in education was analysed. Three categories were distinguished: *Insufficient readiness to use AI*, *Potential for improvement and motivation,* and *Critical/cautious attitude towards AI*. The results are presented in Table 1.

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Table 1

Readiness to Use Artificial Intelligence Technologies

Category	*N* (%)	Subcategory	*N* (%)	Subcategory components	*N* (%)
Insufficient readiness to use AI	64 (57.7)	Lack of knowledge and skills	27 (24.4)	Lack of general knowledge about AI	14 (12.7)
				Do not feel ready	10 (9.0)
				Do not know how to apply AI in the educational process	3 (2.7)
		Lack of experience and practice	22 (19.8)	Lack of practical experience with AI tools	12 (10.8)
				Little attention was paid to AI during studies	4 (3.6)
				Have not yet had the opportunity to use AI in practice	6 (5.4)
		Technological distrust/unpreparedness	15 (13.5)	Do not have practical skills to use AI tools	6 (5.4)
				Used only ChatGPT or very superficially	4 (3.6)
				Afraid to use due to technological barriers/ misunderstanding	5 (4.5)
Potential to improve and motivation	34 (30.6)	Positive attitude and openness to innovations	21 (18.9)	Interested in AI and want to learn	8 (7.2)
				Visible benefits of AI (ideas, planning, teaching tools)	7 (6.3)
				Expect to acquire the necessary competencies during studies	6 (5.4)
		Need for improvement	13 (11.7)	Have basic knowledge, but it must be deepened	6 (5.4)
				Need more practice / deepen knowledge	5 (4.5)
				Use AI for personal needs, but not for education	2 (1.8)
Critical/ cautious attitude towards AI	13 (11.7)	Scepticism, priority for regular learning	13 (11.7)	Doubts about the reliability of AI/ quality of sources	4 (3.6)
				AI can be dangerous / limit the quality of education	3 (2.7)
				AI is not necessary; it is possible to teach without it	2 (1.8)
				Preference for traditional learning	2 (1.8)
				Refuse to use AI (indifference or hostility)	2 (1.8)

Note. 111 semantic units were identified

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As can be seen in the first table, most respondents indicated that they currently felt insufficiently prepared to use AI (57.7%). Lack of knowledge and skills (24.4%) is the most frequently mentioned aspect. Lack of general knowledge about AI is evident (12.7%). In addition, several respondents admitted that they did not feel prepared (9.0 %) or did not know how to specifically apply AI in the educational process (2.7%). The subcategory Lack of experience and practice (19.8%) also has a fairly significant weight. It is emphasised that there is lack of practical experience with AI tools; insufficient attention was paid to the topic of AI during the studies, and some of the respondents still did not have an opportunity to try AI in practice.

Some respondents indicated that they did not have practical skills to use AI; they used it only superficially or felt fear due to technological barriers. On the other hand, a significant part of the respondents show openness and a desire to improve in the field of AI. Some respondents are actively interested in AI (7.2%), see its benefits (6.3%), or hope to acquire the necessary competencies during the studies (5.4%). The need for improvement is much less expressed. The respondents indicate that they have basic knowledge that needs to be deepened, or that more practice is needed. Some are already using AI for personal purposes, but not for education.

„I don't think I'm very prepared because I have a hard time understanding technology and it takes time to figure it out. I prefer books and contact learning" (A).

"My studies have helped me to discover different DI tools, I have had the chance to try out a few, and the only thing left to do is to practise using them" (B).

"I have not tried artificial intelligence technologies, or I am not even sure when artificial intelligence is used, as it is a rather broad term that covers a variety of technologies that are already common in our daily lives" (C).

"In my opinion, I will definitely use AI in my work, but at the moment I don't feel confident in my "ability" to use it properly and effectively, but if I could figure out how and in what ways AI could help me, then I wouldn't be opposed to using it in my job" (D)

A critical/cautious attitude towards AI is rather pronounced as well. Although this group is the smallest, it is still significant. Respondents express scepticism as regards AI. Scepticism and priority for conventional teaching/learning are also expressed. Doubts are usually indicated due to the reliability of AI, possible impact on the quality, or even a negative attitude ("AI is not necessary", 1.8%; "refuse to use", 1.8%).

In summary, it can be stated that more than half of the respondents feel insufficiently prepared to use AI, which is usually related to a lack of knowledge and practice, and technological distrust. However, a third shows motivation to improve, which is a positive prerequisite for change. A small but significant part maintains a cautious or even hostile attitude towards AI, which may be an obstacle to the widespread and effective application of these technologies in education. This allows us to state that it is necessary to strengthen the development of AI competencies both through formal education and through practical training and discussions about the possibilities and risks of AI application.

The position of the respondents on possible/likely challenges using AI in education was also analysed. Four categories were reasonably distinguished: *Pedagogical challenges and quality of education*, *Social, ethical, and psychological aspects*, *Information quality and sources, and Technological* and *infrastructural challenges*. The results are presented in Table 2.

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Table 2

Possible / Expected Challenges of Using AI in Education

Category	*N* (%)	Subcategory	*N* (%)	Subcategory components	*N* (%)
Pedagogical challenges and quality of education	46 (39.0)	Lack of creativity and critical thinking	17 (14.5)	Inhibition/lack of creativity	6 (5.2)
				Lack of critical thinking	3 (2.5)
				Students do not look for answers on their own	2 (1.7)
				Similar ideas	2 (1.7)
				Decreased imagination/effort	2 (1.7)
				Weakened thinking skills	2 (1.7)
		Deterioration of the teaching process	11 (9.3)	Decreased quality of learning	4 (3.4)
				Teachers no longer track progress	2 (1.7)
				Teachers cannot use AI purposefully	2 (1.7)
				Student skills development slows down	2 (1.7)
				Tasks become too simple	1 (0.8)
		A decrease in motivation and independence	10 (8.5)	Lack of independence	3 (2.5)
				Trust in AI instead of one's own strength	3 (2.5)
				Intrinsic motivation decreases	2 (1.8)
				AI "does everything for you"	2 (1.7)
		Lack of competences	8 (6.8)	Teachers lack AI competences	3 (2.5)
				Students do not know how to use AI properly	2 (1.8)
				It is not clear how AI works	2 (1.7)
				It is difficult to formulate queries	1 (0.8)
Social, ethical, and psychological aspects	32 (27.1)	Ethical violations and distrust	9 (7.6)	Ethical issues (privacy, authorship)	3 (2.5)
				Academic dishonesty	2 (1.7)
				Distrust between teachers and students	2 (1.7)
				Abuse of AI	2 (1.7)
		Lack of communication and human connection	9 (7.6)	Lack of live communication	4 (3.4)
				Loss of student-teacher connection	2 (1.7)
				Decreased human interaction	2 (1.7)
				Lack of group work	1 (0.8)
		Dependence and social exclusion	7 (5.9)	Dependence on technologies	4 (3.4)
				Use of AI reduces empathy	2 (1.7)
				AI changes human activity	1 (0.8)
		Psychological and physical consequences	7 (5.9)	More time in front of screens	2 (1.7)
				Physical fatigue (eyes, posture)	2 (1.7)
				Psychological tension/stress	2 (1.7)
				Fear of "imperfection" compared to AI	1 (0.8)

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Information quality and sources	26 (22.0)	Information inaccuracy and reliability	15 (12.8)	False/inaccurate information	6 (5.2)
				Unverified/incomplete sources	4 (3.4)
				Generalised/irrelevant information	3 (2.5)
				AI cannot answer specifically, provides abstractions	2 (1.7)
		Copyright, plagiarism, failure to cite sources	11 (9.3)	Plagiarism	3 (2.5)
				Uncited sources	3 (2.5)
				Inauthentic ideas	2 (1.8)
				Unclear authorship	2 (1.7)
				Copyright violations	1 (0.8)
Technological and infrastructure challenges	14 (11.9)	Technology availability and resources	6 (5.1)	Not all schools have the necessary technologies	3 (2.5)
				Not everyone has access to AI	2 (1.8)
				Internet connection problems	1 (0.8)
		AI performance limitations and restrictions	5 (4.2)	AI does not understand abstract queries	2 (1.8)
				AI cannot respond to emotions	1 (0.8)
				AI does not understand context	1 (0.8)
				AI answers are irrelevant	1 (0.8)
		High time costs when learning with AI	3 (2.5)	It takes time to understand AI	2 (1.7)
				Need to learn to use AI systematically	1 (0.8)

Note. 118 semantic units were identified

The second table shows that the category Pedagogical challenges and quality of education (39.0%) dominates the entire analysis and shows that the impact of AI on the learning process is of greatest concern. There is a noticeable suppression of creativity, similar ideas, a decrease in imagination and effort. Students often no longer try to think for themselves or look for solutions. The deterioration of the teaching process is also evident in the structure of challenges (9.3%). The use of AI in some cases contributes to the deterioration of the quality of learning because teachers are not always able to apply it purposefully, and the development of students' abilities may slow down. The decline in motivation and independence is less pronounced (8.5%). There is a growing reliance on AI instead of one's own strengths, a decrease in intrinsic motivation, and a lack of independence. In addition, both teachers and students often do not have sufficient competencies to use AI or even do not understand how it works.

"Excessive use of AI, less self-work, interaction with learning, and immersion" (E)

"It is possible to overstep the limit and automate too many things" (F)

"If not used properly, it can reduce motivation to study" (G)

"The emergence of a distrust factor between teacher and learner or between lecturer and student" (H).

https://doi.org/10.33225/BalticSTE/2025.133

"Low-quality, inferior content applied/generated" (I)

"Ethical issues (privacy, copyright infringement)" (K)

"Weakening of independent thinking skills and creativity" (L)

Social, ethical, and psychological aspects occupy the second position (27.1%). This shows that the implementation of AI has not only technical or pedagogical, but also significant social consequences. For example, questions arise about privacy, authorship, possible misuse of AI, and academic dishonesty. Lack of communication and human connection (7.6%) is also expressed. It is believed that AI can reduce the possibilities of live communication, weaken the bond between teacher and student, and promote social exclusion. The growing dependence on technology also stands out as a significant challenge, which poses a threat to empathy and the comprehensiveness of human activity. Long-term use of AI can cause fatigue, stress, psychological strain, and distorted comparison with the "more perfect" AI system.

Information quality and sources (22.0%) is also a fairly significant category. The information provided in AI is not always reliable or properly cited. Incorrect, generalised, or unreliable answers pose challenges in checking facts and ensuring the quality of learning. AI increases the risk of plagiarism, as sources are often not provided, authorship is unclear, or inauthentic ideas are presented.

The least prominent category in the category structure is Technological and infrastructural challenges (11.9 %). Despite progress, the application of AI still faces practical barriers. Not all schools have the necessary equipment or internet connection, and not all students can use AI. It is noted that AI often does not understand emotions, context, abstract queries, and its answers may be irrelevant. Also, learning to work with AI requires time and systematic preparation.

The analysis shows that the integration of AI into the education process poses multiple challenges – from pedagogical to social and technological. The greatest risk arises due to possible weakening of thinking, creativity, and motivation, as well as due to growing dependence on AI and decreasing communication. In addition, challenges related to information reliability and copyright are observed. This indicates the need to integrate AI into the educational process in a balanced and responsible way, altogether strengthening the digital, ethical, and critical thinking competencies of teachers and students.

Discussion

The aim of the study was to analyse the readiness of pre-service preschool and pre-service primary education teachers to use AI technologies in the education process, as well as possible and likely challenges they see.

Students indicate that they lack knowledge, experience, or practical skills to use AI. On the other hand, students express a desire to delve deeper into studying AI, participate in trainings or seminars. At the same time, students doubt the benefits of AI, fear its impact on learning, or give priority to ordinary/conventional methods. Most students feel insufficiently prepared to use artificial intelligence (AI) technologies due to a lack of practice and knowledge. Almost a quarter are those who would like

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to improve, but do not yet have sufficient skills. A small proportion of students are sceptical or cautious about AI. Although students have already tried AI for personal purposes, only a very small proportion feel fully prepared to apply it in the teaching process. It is important to note that even those who see the benefits of AI emphasise that its application requires critical evaluation and teacher competence. The study by García-Chitiva et al. (2024) also highlighted factors such as experience of using AI, coding skills, and perception of benefits of AI, which influence readiness. Researchers also found that the biggest concern was the potential decline in students' critical thinking and creativity, information reliability problems, and reduced social interaction. Wang and Chuang (2024) examined the factors influencing students' readiness to use artificial intelligence technology. They found that AI self-efficacy positively correlated with readiness, while anxiety about AI negatively affected readiness. Research shows that meeting psychological needs (autonomy, competence, relatedness) and employing self-regulated strategies, significantly increases AI literacy, which is a key component of readiness to learn (Wang et al., 2025). Furthermore, students are significantly more likely to use AI tools if they believe that these tools improve their academic achievement and learning outcomes (Hoang & Hoang, 2025; Tang et al., 2024; Wu et al., 2022).

The study revealed key challenges related to the use of artificial intelligence (AI) technologies (various platforms, tools, etc.) in education. The challenges identified include the weakening of critical thinking and creativity, information reliability problems (inaccurate answers, failure to cite sources), the weakening of social connections (reduced live communication, loss of teacher influence). The analysis also revealed technical and ethical difficulties (privacy security, dependence on technology, lack of teachers' and students' competences). Furthermore, the uneven availability of AI in schools and the risk that over-reliance on technology will reduce independent thinking and motivation to learn becomes obvious. These challenges require clear guidelines, training, and a balance between the use of AI and conventional educational methods. Despite its potential, the use of AI in education faces serious challenges. One of the biggest is teacher readiness. Many of them do not have enough knowledge and skills to integrate AI into the classroom, and the training offer is still limited. Teachers are also sceptical about automated grading systems because it is not entirely clear how these systems make decisions. Lack of transparency undermines trust in technologies. Similar results have been obtained by other researchers. Many beginning teachers report that they lack formal training in artificial intelligence tools and their integration, resulting in a lack of confidence and readiness to effectively use artificial intelligence in the educational process (Luckin et al., 2022; Zhu & Chen, 2022). Pre-service teachers express concern about data privacy, ethical use of artificial intelligence, and potential misuse of AI-generated content, highlighting the need for ethical guidelines and awareness in the field of AI education (Lamanauskas, 2025; Southworth et al., 2023; Williamson & Eynon, 2020). In addition, preschool and primary education teachers face difficulties in selecting appropriate AI programmes or educational activities that meet educational goals and curriculum requirements (Abualrob, 2025; Pursnani et al., 2023).

This study has several important limitations. First, the study was conducted with a small sample of subjects, and therefore, the obtained results and conclusions are not generalisable. Various demographic factors were also not assessed. The subjects were also students of a very specific field of study, namely, pre-service preschool and primary

https://doi.org/10.33225/BalticSTE/2025.133

education teachers. Further studies should use a more diverse and larger sample to improve external validity.

Conclusions and Implications

A survey of pre-service preschool and pre-service primary education teachers showed that most students feel insufficiently prepared to use artificial intelligence (AI) technologies in the educational process. The greatest lack of preparation is determined by the lack of knowledge, practical skills, and real experience with AI. Students are often not familiar with the possibilities of applying AI in education, and during their studies, little attention is paid to this topic. However, some of the respondents show motivation to learn. They are interested in AI, hope to acquire the necessary competencies during their studies, and are already using some AI tools for personal purposes. However, only a very small proportion feel ready to apply AI in the educational process, and some students remain sceptical or even hostile regarding these technologies.

The study also revealed multiple challenges that teachers may face when integrating AI into education. The dominant challenge is educational: students fear that AI can inhibit students' creativity, critical thinking, reduce motivation, and promote passive learning. Social and ethical aspects are also prominent, as there are concerns about a lack of communication, privacy violations, technology addiction, and academic dishonesty. Another important challenge is the reliability of information: AI provides inaccurate, generalised information, often without citing sources, which poses a risk of plagiarism and disinformation. Technological barriers, such as insufficient equipment, internet accessibility, or AI limitations (inability to understand emotions or context), also hinder smooth integration.

These research results show that to effectively integrate AI into the educational process, it is necessary to strengthen students' AI competencies already during their studies. It is necessary to consistently include AI topics in teacher training programmes, organise practical training, and promote critical evaluation and discussions about the application of AI. It is especially important to form clear ethical guidelines and create support systems for pre-service teachers, from strengthening the technological base to pedagogical consulting. It is also necessary to find a balance between innovative AI solutions and conventional educational methods, so that AI is viewed as an auxiliary tool, and not as an end in itself.

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BRIDGING DISCIPLINES: THE ROLE OF MATHEMATICAL REASONING IN INTERDISCIPLINARY INQUIRY

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Abstract

This study posits mathematics as a fundamental methodological framework for navigating the complexities of multidisciplinary research. It argues that the increasing prevalence of real-world problems demands the integration of knowledge from diverse scientific fields, where mathematics, particularly through the method of analysis and synthesis, provides a crucial constructive framework. While acknowledging the challenges in applying mathematical proficiency across disciplines and the complexities of interdisciplinary collaboration, the paper highlights mathematics' historical versatility and its role as a "mode of rationality" applicable beyond traditional scientific domains. The topic is explored more broadly and deeply through military technology. The study illustrates the practical application of mathematical reasoning and the inherent value-ladenness of multidisciplinary problem-solving. Ultimately, it concludes that cultivating mathematical literacy and embracing analytical methodologies are essential for fostering effective communication and advancing multidisciplinary research to address pressing global issues.

Keywords: *mathematics education, methodological thinking, multidisciplinary research, scientific reasoning, method of analysis and synthesis*

Introduction

Mature scientific disciplines commonly possess well-defined theoretical foundations and established applications, forming the basis for structured teaching, learning, and research practices. However, contemporary educational research increasingly emphasizes the importance of multidisciplinary approaches. Likewise, real-world problems often require synthesizing knowledge from a wide array of fields. Moreover, seemingly well-defined issues are frequently embedded within practical environments, revealing their multidimensional nature. In such contexts, mathematical knowledge can provide a vital constructive framework.

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Historically, calculus evolved from physics and the natural sciences, but its utility extends far beyond, with notable applications in economics, humanities, and social sciences. Numerous practical projects demand considerable mathematical proficiency. Adams and Essex (2018) offer a compelling example, suggesting that a foundational understanding may require at least a three- to five-semester lecture course. Despite its relevance, such extensive mathematical training is often excluded from curricula due to practical constraints.

Even so, solid mathematical competence remains critical for solving numerous practical problems. While curricula often position calculus as a core component of scientific education, mastering it remains challenging. Completing a calculus sequence does not ensure students can apply it effectively in multidisciplinary contexts. As André Weil's example illustrates, true intellectual creativity requires deep knowledge and adaptable thinking (Weil 1969). The most effective approach cultivates an academic environment promoting systematic study and intellectual engagement across diverse problem domains (Aczel, 2006).

In recent decades, multidisciplinary, interdisciplinary, and transdisciplinary research have become prominent (Frodeman et al., 2017; Hadorn et al., 2008). Nevertheless, these terms still have no universally accepted definition or framework. Practical research and development projects often operate within these paradigms, and philosophical and empirical studies aim to clarify their dynamics (Koskinen, 2014; Koskinen & Mäki, 2016). Addressing global issues—such as climate change, pollution, and overpopulation—demands cross-disciplinary collaboration and participation from experts and the public, ideally beginning from the problem-specification phase (Rissanen & Mutanen, 2019). The categorization of problems into multidisciplinary, interdisciplinary, or transdisciplinary domains does not always clarify how solutions should be pursued. Such projects involve collaboration among varied fields and actors (Klein, 2010). Science education's evolution towards fostering broad scientific literacy parallels these needs. Empowering individuals to understand and engage with science supports the competencies for effective multidisciplinary research (Feinstein et al., 2013; Stuckey et al., 2013).

Solutions to practical problems induce changes in real-world contexts, making these problems inherently value-laden (Balsamo 2017; Funtowicz & Ravetz 2008). Every outcome reshapes the practical environment and the approaches to managing problem situations. Consequently, the full spectrum of consequences remains unknowable in advance. While some outcomes may be anticipated, many significant ones may remain unforeseen. Unfortunately, the reactions to these unknown consequences cannot be predicted, implying that the actual impact of solutions can only be fully understood retrospectively. Fisher and Beltran-del-Rio (2017, p. 114) highlighted "the historical range of mathematics as directly applicable to a wide set of phenomena, practices, and developments in many other fields of learning and human endeavor." Their work broadly illustrates mathematics' constructive role across various scientific disciplines and within culture. Thus, mathematics can be viewed as a methodological foundation for multidisciplinary, interdisciplinary, and transdisciplinary research.

Mathematics has a long history of application in solving practical problems. In antiquity, it was instrumental in astronomical calculations. The primary interpretation was utilitarian. Modern science emerged based on the experimental method, integrating

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practical experimentation with the mathematical understanding of experimental data. Furthermore, mathematical modeling could precede case-specific experimentation when appropriate. Key figures in establishing this direction include Galileo Galilei (1564–1642), Isaac Newton (1642–1727), and Gottfried Wilhelm von Leibniz (1646–1716). The mathematical tool they developed, calculus, can be understood as a general problem-solving method (Fisher & Beltran-del-Rio, 2017; Mutanen, 2019).

Viewing mathematics as a general problem-solving methodology compels us to recognize it as a method for conceptualizing and structuring problems. Therefore, mathematics should be understood as a mode of rationality rather than a formal discipline. For instance, Lévi-Strauss employed mathematics to analyze the marriage systems of aboriginal communities (Aczel 2006), underpinning the realism in cubist art (Hintikka 1975; Aczel 2006). In Artificial Intelligence, the challenge of common sense knowledge underscores the importance of analytical reasoning (Copeland 1993; Hofstadter 1999). Consequently, this paper posits that mathematics offers a general methodological framework for rational deliberation, which the method of analysis and synthesis exemplifies (Niiniluoto 2018). The rationale for emphasizing the process of analysis and synthesis stems from the diverse meanings associated with the term "analysis," as Beaney (2021) demonstrates. Therefore, the focus here is to open a discussion on the fundamental human rationality underlying scientific reasoning, which is rooted in the classical method of analysis and synthesis (Mutanen 2019; Lakatos 1976).

Mathematics and Scientific Research

Present-day experimental science is often termed "exact science," a designation that stems from incorporating mathematics (or statistical data) into research reports. However, this label does not fully elucidate the role of mathematics within these sciences, nor its significance in other scientific disciplines. Mathematics holds a central methodological position in both physics and engineering. In English, a more restricted view often equates "science" with the natural sciences, sometimes mathematical or exact sciences. Nevertheless, mathematics, particularly statistics, finds substantial application in fields such as economics and psychology.

Historically, the evolution of mathematics and physics has been deeply intertwined. In physics, a key challenge was to articulate the concept of change, which calculus effectively addresses. The close relationship is evident in the statement: "The acceleration [...] is the rate of change (the derivative) of the velocity, which is in turn the rate of change (the derivative) of the height function" (Adams & Essex 2018, p. 2). Thus, fundamental physics and mathematics (calculus) notions are intrinsically connected. While this connection might become less apparent during a calculus lecture course, it remains a foundational element of calculus theory.

Calculus finds direct application in the natural sciences and engineering. Its development is closely linked to the advancement of physics, providing the logico-conceptual tools necessary to analyze physical phenomena. A core concept like instantaneous velocity relies on the possibility of considering progressively smaller time intervals and displacements, whose logico-mathematical analysis hinges on the notion of a limit. Extending this process indefinitely leads to the concept of infinitesimals (Boyer 1949). However, despite its historical roots in physics, calculus also has significant

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applications in the human sciences (Barnett 2019). This broad applicability arises because calculus solves specific problems regardless of their subject matter. Indeed, calculus textbooks often share similar content, whether intended for natural scientists or those in the humanities.

Mathematics extends far beyond calculus, encompassing a vast and intricate landscape. For instance, Glymour and Cooper (1999) demonstrated the applicability of Bayesian networks across diverse contexts. The Bayesian approach is integral to statistical or probabilistic reasoning, which enjoys widespread use in various scientific fields (Suppes 1969). Bayesian networks are a component of the more general graph theory (Bondy & Murty, 2008), providing a broader framework. Furthermore, in social sciences and economics, game theory (von Neumann & Morgenstern 1944) has numerous applications, such as in decision theory (Raiffa 1970), where mathematical analysis reveals paradoxes inherent in the structure of specific complex decision problems (Campbell & Sowden 1985). Such examples deeply characterize human nature, as preference theory (with its mathematical-logical structure) demonstrates (von Wright 1983). More generally, mathematics is not merely a quantitative or qualitative research tool but a more encompassing methodological discipline that supports all rational human endeavors, such that "not a single area of human interest would be left untouched" (Aczel 2006, p. 57).

While emphasizing the role of mathematics as a methodological tool, it is crucial not to overlook that in scientific research, (applied) methods are not simply instruments. Methods and content engage in a mutual interplay that must be considered from the initial research planning stages. This interaction is also evident in textbooks. For example, Cutnell and Johnson (2005) stressed the importance of "conceptual understanding and problem solving" in physics. Simultaneously, they noted that "physics is often regarded as a collection of equations that can be used blindly to solve problems." What else could calculation-based problem-solving in physics entail? Calculus can be employed as a content-neutral problem-solving mechanism: if a problem exhibits a specific structure, it can be formalized and solved by mechanically applying particular calculations.

Scientific reasoning transcends mere formal rationale; it is inherently contentful. It involves analyzing the problem situation, particularly the phenomenon under investigation. The mathematical representation of physics offers readily available formal solutions. However, relying solely on calculation is insufficient. Unfortunately, homework exercises solvable by direct formula application often provide limited insight into genuine scientific problem-solving. They might be more accurately characterized as quasi-practical problems. In actual practical issues, the initial step involves a thorough analysis of the phenomenon under study, which can be a research-like undertaking (Hintikka & Remes, 1974).

The overall planning of scientific research constitutes part of the methodology. Methodology mathematics is not a specific branch of mathematics but rather a general orientation of scientific rationality. Within a method, the fundamental task is to situate the problem within an intellectual framework. Typically, problems are not well-defined initially, and the primary challenge is to identify the relevant aspects of the problem and determine how they can be addressed. Only after this initial localization can the proper scientific problem specification begin.

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The Method of Analysis and Synthesis

The study of mathematics education has shown considerable interest in mathematical reasoning – the processes involved in reasoning mathematically. The concept of mathematical reasoning is linked to mathematical formalism, as Turing (1939) explicated. Furthermore, Turing (1939, 208-209) discussed the roles of intuition and ingenuity in mathematics. Intuition, in this context, "consists in making spontaneous judgments which are not the result of conscious trains of reasoning." Generally, intuition is often viewed as an alternative to rational reasoning. However, intuition has played a more constructive role in the philosophy of logic and mathematics, as Kant articulated (Hintikka & Remes 1974; Niiniluoto 2018; de Toffoli 2019).

According to Turing (1939, p. 209), "ingenuity in mathematics consists in aiding the intuition through suitable arrangements of propositions, and perhaps geometrical figures or drawings," intended to demonstrate the validity of intuitive reasoning. The foundation of this kind of ingenuity has also been extensively studied in the philosophy of logic (Mumma, 2012). Creativity and intuition have been examined more recently in mathematics education (Kontorovich & Liljedahl, 2018). In education, the focus has often been on empirical aspects of learning, such as psychological or sociological factors, rather than the logico-conceptual aspects of learning mathematics. However, this distinction should not be overstated, as there are apparent structural similarities between the work of Liljedahl (2018) and Jung (1996), although the latter emphasizes methodological aspects. This paper aims to briefly explore the foundations of mathematics, a topic extensively investigated in logic (Jaquette 2002).

For today's education researchers, this paper aims to observe, discuss, and refresh the classical method of analysis and synthesis. The method originated in ancient geometry. In this tradition, the search for proofs of theorems was termed theoretical analysis, while the search for constructions to solve problems was called problematical analysis (Hintikka & Remes 1974). School mathematics commonly illustrates the creative nature of geometrical reasoning. Furthermore, diagrams play a significant role in geometrical reasoning, making it practical. In a geometrical proof, "it seldom suffices to consider the given figure, i.e., the figure of which the antecedent of the proposition speaks" (Hintikka 1973, p. 202). Instead, we require "a 'preparation' or a 'construction' or a 'machinery'" (ibid.) – additional information that completes the proof. Such a method of analysis can be termed constructional analysis (Hintikka 1973, p. 201). Descartes generalized the analysis method from analyzing geometrical figures to analyzing algebraic equations (Mutanen 2019).

Learning objectives have widely been discussed in educational science, with Bloom's taxonomy (Agarwal 2019) serving as a key reference point. Bloom's taxonomy aims to characterize the depth of learning by referring to the hierarchical steps within the taxonomy. This paper focuses on the mathematical structure of the topic, shifting attention from the learner's pure taxonomical state to the logico-conceptual structure of the subject matter. Fortunately, there is a significant interconnection between the two: a deeper level of analysis (in the logical sense) corresponds to a deeper understanding of the original meaning of Bloom's taxonomy. The logico-conceptual approach presented in this study can be applied to analyze the pedagogical approach developed by science education researchers Kokkonen and Mäntylä (2018).

https://doi.org/10.33225/BalticSTE/2025.146

The grand method of analysis and synthesis has not been confined to mathematical reasoning: "Newton – probably the most famous admirer of ancient Greek geometry – assimilated in so many words his experimental method to 'the Method of Analysis'" (Hintikka & Remes 1974, p. 1). The situation is analogous in scientific analysis, but the subject of study is externally given. It is a mathematical fact that no universal method exists for finding the best constructions in geometry, implying that geometrical reasoning is inherently creative (Hintikka 1973, p. 203). The situation in physics is structurally similar, even though physics addresses factual matters in a well-established manner.

Thus, analysis is a research-like process. Constructing the experimental setup in experimental physics corresponds to creating an analytical geometrical proof. However, just as in geometry, the theoretical background knowledge guides the construction of the experimental setup. Unfortunately, there is no guarantee that optimal construction will be achieved. There are two primary reasons for this. Firstly, the practical reason is the theoretical challenge of identifying the most fundamental questions (parameters) in an experimental situation. Secondly, the theoretical reason is that there are no assurances that the analysis can be completed.

Developers of educational materials must acknowledge the inevitability of misconceptions among learners, even with thoroughly tested materials. However, these misconceptions can serve as a valuable foundation for clarifying discussions and knowledge formation. Logical reasoning and its specific manifestations are essential to exercises and problem-solving in education. Many problems (e.g., in physics) can be solved using nonstandard methods or intuition (Belikov 1986). Nevertheless, standard methods typically yield more systematic results. Therefore, students must develop the ability to analyze (physical) phenomena and understand how to formulate a standard approach to solutions. Moreover, exercises aim to foster students' creative thinking (Sena 1988). The rote repetition of relatively simple mathematical tasks embedded in a superficial context may create a false sense of acquired skills. Conversely, tasks that are overly demanding and lack sufficient support may obscure the practical significance of calculus. Consequently, the type and number of similar exercises need to be carefully adjusted to the knowledge level of the student group and the available resources for practice.

Multidisciplinary Research in Military Education

In multidisciplinary research endeavors, the complexity of the situation can be considerable. For instance, global warming exhibits extreme multiplicity, challenging the identification of foundational facts due to the measurement procedures' theory-laden nature. Furthermore, even the designation of field experts can be contentious (Lindzen 2017). Addressing global warming necessitates knowledge integration from diverse scientific domains, expertise from various practical fields, and the application of new or emerging technologies. Consequently, solutions are invariably intricate amalgams of knowledge, skills, and values derived from disparate sources (Balsimo 2017).

To render the discussion more manageable, we will consider a more circumscribed case: military technology. This example illuminates several intriguing facets of multidisciplinary research. Military technology represents a domain of expertise that intricately connects technology, planning, leadership, and education. Moreover, proactive efforts are often made to incorporate user experiences during the planning

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phase within military technology, which characterizes military technology projects as transdisciplinary.

Let's undertake a concise philosophical analysis of military technology projects. Historically, military technology has been considered a leading edge area of expertise and developmental aims. While technology has sometimes been described as applied science, Dusek (2006, p. 33) correctly points out that this represents only a partial truth at best. Fundamentally, science is categorized as basic science, defined as "the systematic pursuit of new scientific knowledge without the aim of specific practical application" (Niiniluoto 1993, p. 2). In contrast, applied science is "the pursuit of knowledge to obtain a specific goal" (ibid.). Technology, however, is not merely such a pursuit but rather an integral component of development, which seeks "new products, methods, and means of production" (ibid.) based on the findings of both basic and applied sciences.

It is instructive to delineate different research approaches based on the fundamental utilities they prioritize. In this context, basic science is fundamentally an epistemic endeavor, where epistemic utility constitutes the paramount value or utility. The primary objective is the acquisition of novel knowledge about reality. While epistemic utilities are also present in applied science, these endeavors concurrently aim for various forms of practical utility. Applied science thus seeks not only truthful knowledge but also tangible benefits. In the realm of technology, and more broadly in development, the emphasis shifts firmly towards practical utilities (Niiniluoto 1993), with knowledge primarily holding instrumental value. Indeed, members of the Frankfurt School extended this perspective to encompass all scientific endeavors (Dusek 2006). In military technology education, an initial, concise review of mathematics and physics at the high school curriculum level is often undertaken to provide practical analytical tools for examining complex phenomena. Consequently, successful military technology represents a synthesis of science-based technology, military leadership, and military pedagogy. The requisite mathematics for studying each element includes calculus, game theory, and graph theory. While mastery at a professional level falls outside the scope, the aim is to cultivate thinking and analytical proficiency for future engagement with unforeseen problems.

The Origin of Logic in Technology

Technology, particularly contemporary high technology, is in some sense science-based. However, precisely delineating the relationship between science and technology can be challenging. Significant technological development still occurs without a discernible connection to scientific knowledge. To analyze this relationship more closely, let us consider the technical norm articulated by Georg Henrik von Wright and formulated by Niiniluoto (1993):

Technical norm: If you want A, and believe you are in a situation B, then you should do X.

That is, technical norms express "technical oughts" that are only binding if the antecedent conditions are accepted – if one adopts A as a desired goal and believes the current situation to be B.

https://doi.org/10.33225/BalticSTE/2025.146

Technical norms rest on the assumption that X is feasible, which necessitates that the technology is, to a significant extent, under the agent's control. This can be termed the manipulativity condition. Furthermore, the agent believes that, in situation B, X causally leads to A. This causal relationship is fundamentally a product of experimental science. For instance, in the context of global warming, there is an underlying assumption that the international atmosphere is manipulable by human actions. Indeed, a substantial body of scientific knowledge demonstrates how human behavior has altered the climate.

The technical norm highlights the inherent value-laden nature of technology. Values are explicitly articulated within technical norms. However, a more in-depth analysis of the values underpinning these norms requires further investigation in each specific case. The preceding characterization reveals that analyzing a technological problem necessitates knowledge from diverse, case-specific fields of expertise. We have already mentioned scientific knowledge, which can be drawn from various scientific disciplines depending on the technological problem. Given that military technology is typically deployed in extreme situations, its study inherently involves multiple scientific fields, as previously noted. The other domain of expertise mentioned was ethics (values). How can values be integrated into the solution of a technological problem? Is it sufficient for the final decision-making process to take them into account?

Bunge (2006, p. 178) characterized technological problems as frequently being reverse engineering problems that "are typically design or maintenance problems." Technology has been classified as part of the so-called design sciences (Simon 1968; Niiniluoto 1993; Galle & Kroes 2014). Design is an activity initiated by a preliminary concept of a desired outcome, often with imprecisely defined goals and constraints that must be satisfied. These constraints can be diverse, encompassing factors such as final cost, materials employed, or practical usability. Even within the often chaotic and knowledge-deficient context of military operations, a significant body of general knowledge adequately specifies usability constraints. For example, these constraints might define the extreme conditions under which the technology-human system must function effectively.

The design process serves as an excellent illustration of the method of analysis previously characterized. Design might commence with the envisioned end product that meets all specified constraints. The study then progressively delves into the product's structure, elaborating on increasingly finer details until all relevant aspects are defined. Upon completion of the analysis, explicit knowledge regarding the product's construction, required materials, and inherent properties is obtained. Naturally, depending on the imposed constraints, all potential side effects will also have been elucidated. Before commencing production, all the knowledge and details about the construction process must be thoroughly evaluated. For the described task here, military technology education projects provide valuable examples where different facets of the planning process can be exercised in multidisciplinary ways.

Discussion

This exploration has underscored mathematics' indispensable role as a foundational methodology for navigating multidisciplinary research complexities. The increasing prevalence of real-world problems transcending disciplinary boundaries necessitates

https://doi.org/10.33225/BalticSTE/2025.146

knowledge integration, where mathematics, provides a framework for conceptualizing intricate scenarios. Recognizing that mathematical mastery doesn't automatically ensure practical multidisciplinary application highlights the need for intellectual flexibility and environments fostering systematic study. (Aczel 2006.) The prominence of multidisciplinary, interdisciplinary, and transdisciplinary research, driven by global challenges, further emphasizes the need for frameworks bridging disciplinary divides. While definitions and approaches vary, practical knowledge integration and diverse expertise are crucial (Rissanen & Mutanen, 2019). The inherent value-laden nature of real-world solutions (Balsamo 2017; Funtowicz & Ravetz 2008) adds complexity, demanding consideration of non-obvious consequences. Analyzing mathematics as a methodological tool beyond computation reveals its capacity as a "mode of rationality" (Niiniluoto 2018). Its application in diverse fields illustrates its power in structuring complex systems. Emphasizing analysis and synthesis, rooted in geometry and adopted by scientific pioneers (Hintikka & Remes 1974), highlights a fundamental problem-solving approach in mathematical and scientific reasoning. Exploring mathematical logic, including intuition and ingenuity (Turing 1939), enriches understanding of complex problem-solving.

The military technology and its education offer a multidisciplinary field integrating technology, planning, leadership, and education. Applying the "technical norm" (Niiniluoto 1993) reveals the value-ladenness of technological development and the need for ethical considerations alongside scientific and practical aspects. The design process in military technology exemplifies analysis, moving from desired outcomes to detailed specifications. Unifying languages and theories across disciplines in multidisciplinary research is challenging (Tuomela 1973; Niiniluoto & Tuomela 1973; Stegmüller 1976). While examples like physical chemistry exist, many situations require navigating distinct conceptual landscapes. Without universal solutions, respectful dialogue and effective communication are paramount (Heinonen 2017), highlighting the importance of mathematical reasoning in facilitating this and fostering science literacy.

Conclusions

This study explores the methodological advantages of mathematics in tackling complex challenges, particularly in structuring research and addressing logically defined tasks. A perspective on broad applicability and connection to scientific reasoning is presented through analysis and synthesis. The mathematical-logical examination emphasizes the method's ability to provide a unifying framework for diverse research. The complexities of integrating knowledge, particularly in terms of unifying languages and theories, necessitate a focus in research activities on promoting communication and shared analytical approaches. Ultimately, developing mathematical literacy and embracing analysis and synthesis are crucial for advancing effective multidisciplinary research and solving global problems.

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Declaration of Interest

The authors declare no competing interest.

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SCIENCE EDUCATION FOR STUDENTS WITH SPECIFIC LEARNING AND ATTENTION DISORDERS: AN EVALUATION OF READING STRATEGIES USING EYE-TRACKING TECHNOLOGY

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Abstract

This case study examined how students with learning (dyslexia) and attention deficit process science texts under different instructional design conditions using eye-tracking technology. The aim was to examine the impact of seductive details and visual enhancement elements on reading behaviour and cognitive load. A qualitative case study was conducted with three neurodivergent students and one neurotypical participant (ages 11–14), each exposed to four conditions: plain text, highlighted text, infographic, and decorative image. Eye-tracking data revealed that neurotypical reading was efficient, with short fixations, minimal regressions, and focused attention. In contrast, neurodivergent students exhibited disorganized scanpaths, particularly under conditions involving infographics and decorative images. Highlighted and plain text conditions supported more structured reading, especially for the student with dyslexia. The results suggest that seductive details increase extraneous cognitive load and distract attention in students with cognitive vulnerabilities, whereas signaling via text highlighting may partially support comprehension. These findings highlight the potential of eye-tracking to inform inclusive instructional design and emphasize the importance of minimizing irrelevant visual input in science education materials.
Keywords: *attention-deficit disorder, specific learning disorder, reading difficulties, eye-tracking technology, scanpath comparison*

Introduction

Success in learning builds self-confidence and helps achieve goals. One of the first goals in school is to learn reading, counting, and correct speech (Bellocchi et al., 2013; Church et al., 2023). Reading integrates visual, attentional, and oculomotor processes, not just linguistic ones (Schuett et al., 2008). Already in 1879, ophthalmologist Louis Émile Javal observed eye movements during reading, noting they differed from usual gaze behaviour (Prabha et al., 2019). Since the 1970s, infrared-based eye-tracking (ET) technology has enabled objective analysis of how students process texts and direct attention (Angele & Duñabeitia, 2024; Y. Chen et al., 2023). Nowadays, developing eye-tracking technology (hereafter referred to as ET) offers numerous advantages, primarily due to its non-invasive nature. In contrast to traditional methods of identifying not only cognitive processes but also learning difficulties, ET is more time-efficient and generally reduces stress for participants, thereby potentially minimizing error rates and

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data distortion linked to stress. Besides, traditional questionnaires rely on subjective interpretations of results and are often not adapted to linguistic or cultural diversity. Beyond ET benefits, this method allows participants to engage in research tasks directly on a computer screen with minimal effort and enables the collection of quantitative data that objectively contributes to studies of reading behaviour, attention distribution and identification of learning difficulties (Coenen et al., 2024; Toki, 2024). In recent years, ET has been widely applied in fields such as advertising and communication, particularly for evaluating the effectiveness of marketing strategies (Bauer & Hantel, 2022; Grigaliūnaitė & Pilelienė, 2015), in clinical studies, including those focused on oculomotor changes associated with dementia (Norouzi et al., 2025), neurodegenerative conditions (Marandi & Gazerani, 2019), and reading impairments such as dyslexia (Toki, 2024).

Reading is a cognitively demanding task involving eye movements to gather visual input and extract meaning (Mohammadhasani et al., 2020). It has been discovered that reading skills are heritable and some genes have been found to be associated with reading difficulties (Church et al., 2023). Dyslexia is a learning disorder associated with neurological differences affecting phonological and language processing (Daniutė & Staliūnienė, 2021). People with dyslexia often report oculomotor issues, such as "jumping lines" or blurred text, despite normal vision and average intelligence. These issues impair cognitive processing and affect reading and writing. Early diagnosis is critical due to the brain's plasticity in early age (Bellocchi et al., 2013; Coenen et al., 2024; Toki, 2024).

Attention-deficit/hyperactivity disorder (ADHD) is a chronic neurodevelopmental disorder marked by difficulties in attention and behavior regulation (Lee et al., 2023). Mohammadhasani et al. (2019) recorded that these impairments are also linked to working memory deficits and abnormal eye movements. Eye-tracking may support the diagnosis of comorbid dyslexia in individuals with ADHD (Caldani et al., 2022).

Reading is essential in science education, where texts often include technical language and are supported by graphs, diagrams, and tables (Toki, 2024). As noted by Tosun (2022), learning natural sciences requires higher-order thinking, such as critical thinking and problem-solving. Students have to make interpretations of complex natural phenomena visually presented in schemes. Rapid science discoveries and information updates create challenges even for neurotypical students, and these are amplified for those with special educational needs.

Learning materials now often include design elements like seductive details, images, infographics, and highlighted text. While these can boost engagement and motivation, their impact on learning depends on relevance and cognitive load. Seductive details – interesting but irrelevant – can distract learners and increase extraneous load, especially for those with low prior knowledge (Eitel et al., 2019; Harp & Mayer, 1998; Wesenberg et al., 2025). Though they may spark interest, their effect on retention and application is mixed (Schneider et al., 2019; Stark et al., 2024; Sundararajan & Adesope, 2020; Wang & Adesope, 2016; Wesenberg et al., 2025). In contrast, well-designed infographics and highlights that relate to key content reduce cognitive load and aid comprehension (Çaka & Dursun, 2022; Dogomeo & Aliazas, 2022; Majooni et al., 2018; Ponce et al., 2022; Wu & Liu, 2024). Based on dual coding theory, these elements support learning by combining verbal and visual input, helping build long-term memory (Clark & Paivio, 1991; Mayer, 2024).

https://doi.org/10.33225/BalticSTE/2025.158

Cognitive Load Theory (CLT) explains how the limits of working memory affect learning (Sweller, 2024). It distinguishes intrinsic, extraneous, and germane load, emphasizing the need to reduce unnecessary load and support meaningful processing (Hanham et al., 2023). Baddeley's (2003) model views working memory as a multi-part system for storing and manipulating information. Cowan (2001) notes its limited capacity, especially relevant for learners with attention or learning difficulties. Clear visuals and infographics can reduce extraneous load and enhance cognitive engagement.

Eye-tracking research builds on the eye–mind hypothesis, which links gaze behavior with cognitive processing (Just & Carpenter, 1980). Fixation duration and saccades often indicate effort or confusion. In multimedia learning, Mayer's theory emphasizes balancing visual and verbal input to optimize learning and reduce overload (Mayer, 2024; Mayer & Moreno, 2003). For students with learning difficulties, success depends on how well materials fit their cognitive capacities. Self-Determination Theory (SDT) adds that autonomy, competence, and relatedness support motivation (Deci & Ryan, 2000). Relevant visual aids can reduce stress and improve engagement, while irrelevant ones may increase cognitive load.

Donmez (2023) reviewed 48 studies on ET in special education, mostly focused on dyslexia and autism. Key learning areas included reading, language, math, communication, motor skills, and navigation. ET was shown to help adapt learning environments based on students' observed behaviors. Chan et al. (2022) found that ET-based training improved memory, reading, and learning speed in students with learning difficulties, including ADHD, compared to regular remediation.

Typical reading scanpaths follow a left-to-right, top-to-bottom pattern (Schuett et al., 2008). Caldani et al. (2022) found that children with dyslexia or ADHD show longer fixations, more saccades, and slower reading compared to neurotypical peers. Key eye-tracking metrics include total reading time, fixation count and duration, and regressions (Luegi et al., 2011). Longer fixation durations are associated with increased information processing, cognitive effort, and engagement, and are typically interpreted as indicators of higher cognitive load (Coskun & Cagiltay, 2022; Ke et al., 2024; Liu & Cui, 2025; Negi & Mitra, 2020). A higher number of fixations may reflect greater learning engagement and sustained attentional focus, suggesting an elevated level of cognitive load (O. Chen et al., 2023; Coskun & Cagiltay, 2022; Ke et al., 2024; Mateja & Borawska, 2024). Longer or wider saccades are indicative of more intensive visual exploration or transitions between areas of interest or sources of information (Coskun & Cagiltay, 2022; Mateja & Borawska, 2024). A higher number of regressions suggests processing difficulties, cognitive confusion, or challenges in decoding textual information (S. Chen, 2024; Donmez, 2023; Toki, 2024).

Luegi et al. (2011) offered an additional measure called *Progression-Path,* measuring forward reading effort in critical regions. However, it has not been tested with neurodivergent students. Nagarajan et al. (2023) found that the chronological sequence of gaze fixation and saccades, called scanpath, can be addressed as a distinguishing tool for identifying good and poor readers. Similarly, Coskun and Cagiltay (2022), Krejtz et al. (2018), and Sáiz-Manzanares et al. (2021) declare that scanpath reflects attention strategies and response timing, offering insights into cognitive processing.

https://doi.org/10.33225/BalticSTE/2025.158

Research Problem

Students with specific learning and attention disorders, such as dyslexia and ADD or ADHD, often struggle with reading and processing complex scientific texts. However, little is known about how their visual attention and cognitive processing – especially in science education contexts – are influenced by instructional design elements like seductive details: pictures, infographics, and highlighted text areas. This study addresses the gap by using eye-tracking technology to examine how these students visually engage with scientific content and how seductive details affect their reading behaviour and cognitive processing patterns, using eye-tracking technology. Also, this study expands on earlier research analysing heatmaps of a single student with dyslexia (Raudoniūtė, 2025), by examining scanpath patterns of three neurodivergent learners, including the previously studied case.

Research Focus

The study focuses on evaluating how students with specific learning (dyslexia) and attention (ADHD) disorders visually process scientific educational content using eye-tracking technology. It explores the impact of educational design – specifically the presence or absence of additional instructional elements – on their reading behaviours, such as scanpath patterns, fixation durations, and regressions, to better understand possible cognitive load and reading strategies in science education contexts.

Research Aim and Research Questions

The aim of this research was to study how students with specific learning and attention disorders (dyslexia and ADHD) process science education texts using eye-tracking technology, with a particular focus on how seductive details influence their visual attention, reading strategies, and cognitive load. According to this aim, a few research questions were formulated. First is how do students with dyslexia and attention deficits or ADHD differ in their eye-tracking metrics (e.g., fixation duration, regressions, scanpath) when reading scientific texts compared to typical readers? Second, what is the effect of seductive details on the reading behaviour and attention distribution of students with dyslexia and attention disorder or ADHD while engaging with science content with or without additional enhancing instructional elements? The third question is whether an eye-tracking analysis of scanpath provides insight into the educational design needs of students with specific learning difficulties in science education.

Research Methodology

General Background

This study employed a qualitative case study approach to explore how students with specific learning and attention disorders visually engage with scientific texts presented under different instructional enhancement conditions. The case study design was chosen for its strength in capturing in-depth, context-sensitive insights into eye movements and

https://doi.org/10.33225/BalticSTE/2025.158

cognitive processing during reading. Focusing on three neurodivergent students and one neurotypical student, the research examined their scanpath behaviors as they interacted with science texts containing seductive details, highlighted segments, infographics, or no enhancements. By selecting a real classroom-like setting and integrating eye-tracking data, this methodology allowed for a nuanced understanding of how educational design influences attention allocation and cognitive load among diverse learners.

Sample

This case analysis constitutes a separate part of a broader study that initially focused on neurotypical students. In the original study, a total of 49 students participated; however, three of them reported having special educational needs. As a result, their data were excluded from the main study and instead examined through an individual case study approach. The performance of these three neurodivergent students was compared to the remaining 46 neurotypical participants. A targeted convenience sampling method was used, focusing on students aged 11 to 14 years. The participants were 5th to 8th grade students attending a private general education school in Lithuania. This age group was selected based on Skurvydas et al. (2023), who note that students within this developmental period typically possess sufficient reading and analytical skills, while still actively developing the capacity for self-regulated learning. Moreover, 11–14-year-olds are considered a suitable age group for examining the effects of cognitive load, as their working memory capacity is still maturing and remains sensitive to extraneous information. This developmental sensitivity made it possible to explore how educational material design influences attention and reading patterns. Among the three neurodivergent participants, one 5th-grade student reported a diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder. The second participant, a 7th-grade student, was diagnosed with specific learning disorders (dyslexia). The third, an 8th-grade student, reported both specific learning disorders (reading and writing) and an attention disorder. Written parental consent was obtained in advance via email, following an informational letter outlining the study's purpose and ethical guidelines. Participation was entirely voluntary. All student data were anonymized using participant codes to ensure confidentiality. The study was approved and conducted in accordance with ethical standards for research involving minors.

Instrument and Procedures

The educational content used in the study was adapted from a 6th-grade natural sciences textbook ("Horizontai", Part 2, pp. 62–65, 2024 edition, Šviesa publishing house). It consisted of four brief science texts on adolescent brain development, each modified with a different instructional enhancement:

- an emotionally engaging but irrelevant image (seductive detail),
- highlighted key information,
- an infographic summarizing the key content visually,
- a control text with no additional design elements.

Each text was followed by two comprehension questions: one assessing knowledge and understanding, and the other assessing information application. Both questions were

https://doi.org/10.33225/BalticSTE/2025.158

directly related to the content displayed on screen. However, in this case study, test results (correct and incorrect answers to the questions) and learning outcomes will not be discussed.

Due to limitations in the RealEye system, each text was presented twice per session – once before each question – leading some participants to skip re-reading during the second exposure, a natural behaviour acknowledged in the analysis.

The eye-tracking platform RealEye was used to monitor participants' gaze paths via computers (laptops), requiring only a web camera and internet access. While the system records various quantitative metrics, this case study focused specifically on the interpretation of scanpath data to understand reading patterns and strategies.

The procedures were conducted in a quiet, well-lit classroom. Laptops with connected mice were prepared, and students were seated individually. The entire session lasted approximately 15 minutes per participant. During this time, the RealEye platform recorded gaze data while participants read and answered questions. No material compensation was offered; however, students were informed that they could later review their personalized gaze recordings if they participated in a follow-up session.

Data Analysis

Although this study employed a qualitative case study approach, the analysis incorporated visual data captured through the RealEye platform (https://www.realeye.io/), which records the gaze behaviour during the reading process. The primary analytical focus was placed on scanpath visualizations, which allowed for a qualitative interpretation of students' attention patterns, reading strategies, and cognitive load.

While no statistical analysis was conducted in the traditional sense, the scanpath inherently contained quantitative indicators embedded within the visualization, such as fixation duration, sequence, and saccade direction. For example, orange dots in the scanpath represent fixations – the points at which the reader's gaze pauses. The size of each dot correlates with fixation duration, where smaller dots indicate brief glances and larger dots show longer visual engagement, typically associated with higher cognitive effort. The sequential numbering of fixations reflects the temporal order of gaze, thus revealing whether the reading was linear, regressive, organised, or chaotic. Lines connecting the dots, known as saccades, show the movement between fixation points, and zigzag or backward saccades (regressions) were interpreted as indicators of re-reading, difficulty integrating information, or information search behaviour.

This interpretive framework enabled the researcher to derive both visual and cognitively meaningful insights from each student's reading behaviour. The analysis compared the visual attention patterns of three neurodivergent students to a neurotypical student across four instructional formats, focusing on how each condition influenced scanpath structure, attention distribution, and reading strategies. This integrated approach provided a rich, process-oriented understanding of reading behaviour in a science education context, without relying on statistical tests or aggregated group comparisons.

https://doi.org/10.33225/BalticSTE/2025.158

Research Results

E1, E2 and E3 are the abbreviations for the students with learning difficulties (E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder, E2 was diagnosed with specific learning disorders (specifically – dyslexia); E3 was diagnosed both specific learning disorders (reading and writing) and an attention disorder). Letter "T" stands for the case of a neurotypical student to compare the scanpath results.

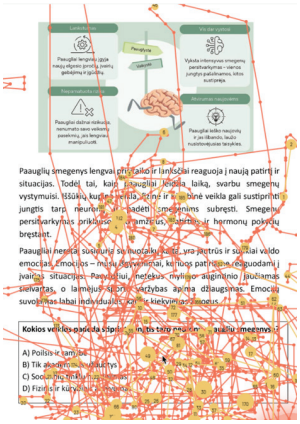
In Figure 1, all participants viewed a text accompanied by an infographic. E1's scanpath is chaotic and widely dispersed, with small fixation points and long, erratic saccades – indicating re-reading and disorganized attention. E2's scanpath is more structured, with fixations mostly on the text, though zig-zag regressions suggest difficulty following lines, consistent with dyslexia. E3's scanpath is scattered across both text and infographic, showing frequent, non-linear shifts and wide regressions – signs of attention difficulty and trouble selecting relevant content.

In contrast, the neurotypical student's scanpath is linear and efficient, moving left to right with minimal regressions. The text and infographic are clearly segmented, and fixations focus on key sentences. After reading, the question area was scanned, followed by targeted regressions to retrieve specific answers. This pattern reflects low cognitive load and well-developed reading comprehension.

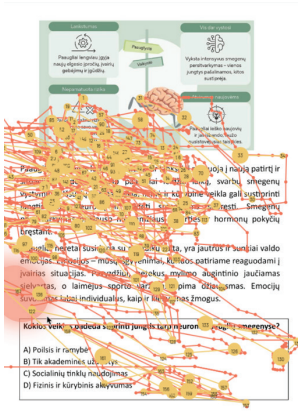
https://doi.org/10.33225/BalticSTE/2025.158

Figure 1

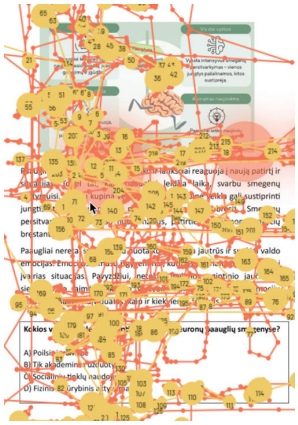
Infographic With Retention (First) Question



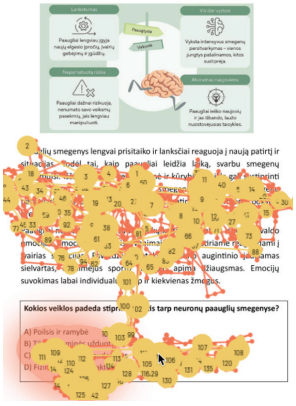
E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder



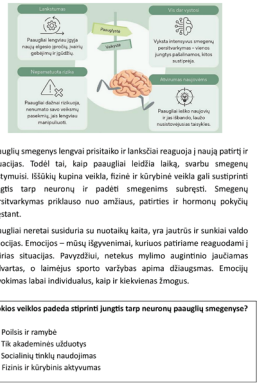
E2 was diagnosed with specific learning disorders (dyslexia)



E3 both specific learning disorders (reading and writing) and an attention disorder.



Neurotypical (T)



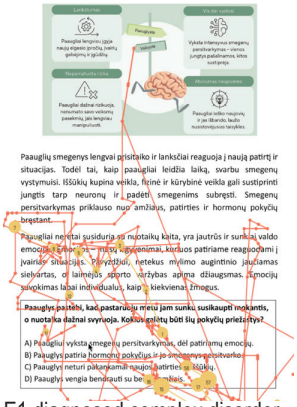
Example of the exercise

Note. The text provided in the exercise: In the infographic: “Flexibility: adolescents more easily acquire new behavioral habits, abilities, and skills. Still Developing: intensive brain restructuring is taking place – some connections are removed, others are strengthened. Unmeasured Risk: adolescents often take risks without foreseeing the consequences of their actions, making them easier to manipulate. Openness to New Experiences: adolescents seek novelty and test boundaries, often breaking established rules”. Main text: “Teenage brains adapt easily and respond flexibly to new experiences and situations. Therefore, how adolescents spend their time is important for brain development. Activities full of challenges, physical activity, and creative tasks can strengthen the connections between neurons and support brain maturation. Brain restructuring depends on age, experience, and hormonal changes during adolescence. Adolescents often experience mood swings, are sensitive, and have difficulty managing emotions. Emotions are our inner experiences, felt in response to different situations. For example, losing a beloved pet brings grief, while winning a sports competition brings joy. The perception of emotions is highly individual, just like each person.” Question: “Which activities help strengthen the connections between neurons in the adolescent brain?” Answer options: “A) Rest and relaxation, B) Only academic tasks, C) Using social media, D) Physical and creative activity”.

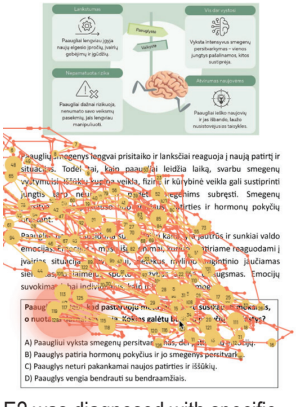
https://doi.org/10.33225/BalticSTE/2025.158

Figure 2

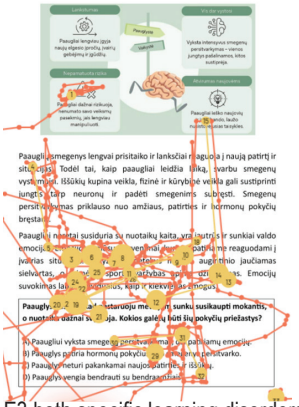
Infographic With Transfer (Second) Question



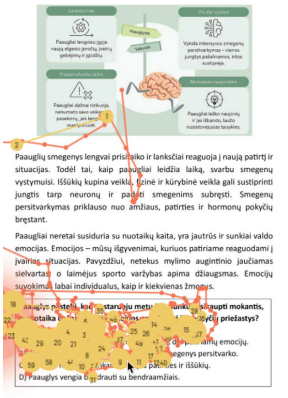
E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder



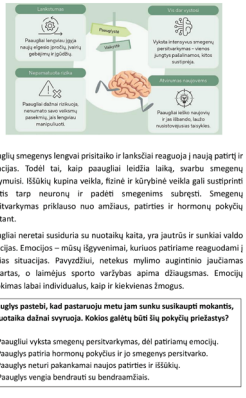
E2 was diagnosed with specific learning disorders (dyslexia)



E3 both specific learning disorders (reading and writing) and an attention disorder.



Neurotypical (T)



Example of the exercise

Note. The same infographic and text. Only transfer question and answer options have changed: "A teenager notices they have trouble concentrating while studying and experience frequent mood swings. What could be the causes of these changes?A) The adolescent's brain is restructuring, and they are experiencing emotions. B) Hormonal changes and brain restructuring are occurring. C) The adolescent lacks enough new experiences and challenges. D) The adolescent avoids socializing with peers."

Figure 2 presents the scanpath for the same infographic condition but with a different – transfer – question. As noted, although the learning content remains the same as in Figure 1, all three divergent students (E1, E2, and E3) tend to read the text once again, while the neurotypical student only glances at the text passage to make sure it is the same information and never came back later.

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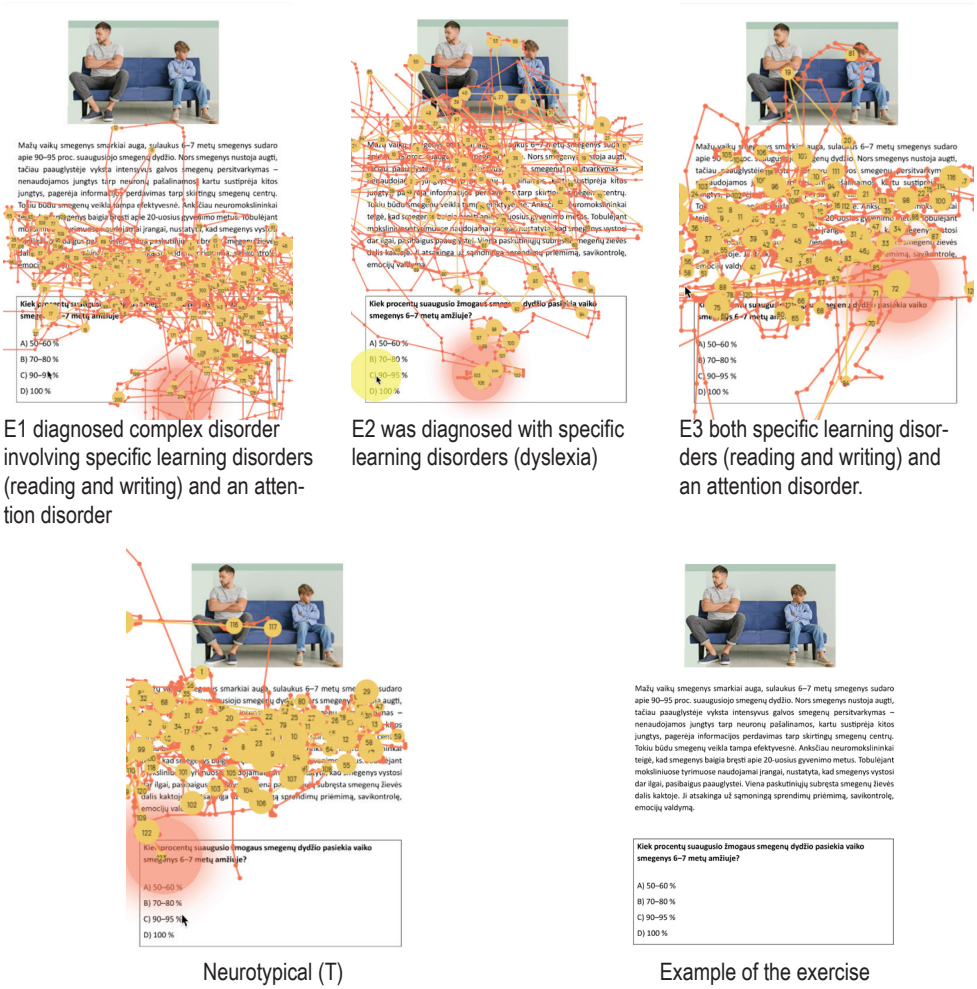
Figure 3

Picture With Retention Question


Mažų vaikų smegenys smarkiai auga, sulaukus 6–7 metų smegenys sudaro apie 90–95 proc. suaugusiojo smegenų dydžio. Nors smegenys nustoja augti, tačiau paauglystėje vyksta intensyvus galvos smegenų persitvarkymas – nenaudojamos jungtys tarp neuronų pašalinamos, kartu sustiprėja kitos jungtys, pagerėja informacijos perdavimas tarp skirtingų smegenų centrų. Tokiu būdu smegenų veikla tampa efektyvesnė. Anksčiau neuromokslininkai teigė, kad smegenys baigia brėsti apie 20-ousius gyvenimo metus. Tobulėjant mokslinimetyrimuose naudojamai įrangai, nustatyta, kad smegenys vystosi dar ilgai, pasibaigus paauglystei. Viena paskutiniųjų subręsta smegenų žievės dalis kaktoje. Ji atsakinga už sąmoningą sprendimų priėmimą, savikontrolę, emocijų valdymą.
Kiek procentų suaugusio žmogaus smegenų dydžio pasiekia vaikų smegenys 6–7 metų amžiuje?
A) 50–60 %
B) 70–80 %
C) 90–95 %
D) 100 %

E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder

E2 was diagnosed with specific learning disorders (dyslexia)

E3 both specific learning disorders (reading and writing) and an attention disorder.

Neurotypical (T)

Example of the exercise

Note. The text: "Children's brains grow rapidly, and by the age of 6–7, they reach about 90–95% of an adult brain's size. Although the brain stops growing, adolescence involves intense brain reorganization – unused neural connections are eliminated, while others are strengthened, improving information transfer between different brain areas. This makes brain functioning more efficient. Previously, neuroscientists believed that the brain finishes developing around the age of 20. However, new technologies have shown that development continues even after adolescence. One of the last regions to mature is the prefrontal cortex, which is responsible for decision-making, self-control, and emotion regulation." Question and answer options: "What percentage of adult brain size does a child's brain reach by age 6–7?A) 50–60%. B) 70–80%. C) 90–95%. D) 100%"

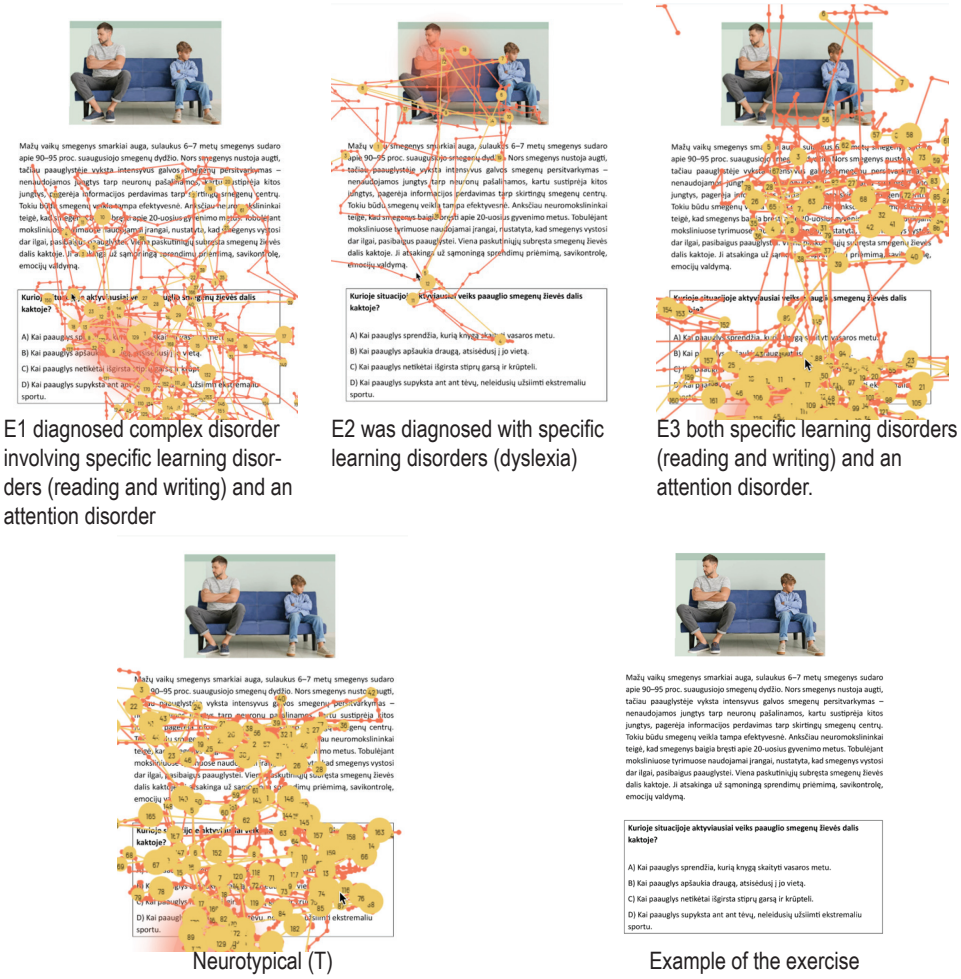
Figure 3 displays the learning material with an irrelevant (decorative) image at the top and a retention question below the text. E1's scanpath was focused on the lower part of the text and the question area, showing fragmented reading but no visual engagement with the picture. E2's scanpath was widely dispersed and less linear, with multiple fixations on the image – especially the man's and boy's body language and the

https://doi.org/10.33225/BalticSTE/2025.158

boy's face – indicating distraction. Despite this, E2 accessed the question area directly after reading, without regressions. E3 also fixated on the image midway through the text, particularly on the crossed arms and facial expressions, but showed difficulty sustaining a coherent reading path, as indicated by scattered, non-sequential fixations. In contrast, student T demonstrated an efficient reading strategy: a quick glance at the picture after finishing the text, followed by a direct transition to the question. T's scanpath was linear, left-to-right, with moderate fixation density and minimal regressions.

Figure 4

Picture With Transfer Question


Mažų vaikų smegenys smarkiai auga, sulaukus 6–7 metų smegenys sudaro apie 90–95 proc. suaugusiojo smegenų dydžio. Nors smegenys nustoja augti, tačiau paauglystėje vyksta intensyvus galvos smegenų persitvarkymas – nenaudojamos jungtys tarp neuronų pašalinamos, kartu sustiprėja kitos jungtys, pagerėja informacijos perdavimas tarp skirtingų smegenų centrų. Tokiu būdu smegenų veikla tampa efektyvesnė. Anksčiau neuromokslininkai teigė, kad smegenys baigia brėsti apie 20-uosius gyvenimo metus. Tobulėjant mokslinėms tyrimuose naudojamai įrangai, nustatyta, kad smegenys vystosi dar ilgai, pasibaigus paauglystei. Viena paskutinių subręsta smegenų žievės dalis kaktoje. Ji atsakinga už sąmoningą sprendimų priėmimą, savikontrolę, emocijų valdymą.
Kurioje situacijoje aktyviausiai veiks paauglio smegenų žievės dalis kaktoje?
A) Kai paauglys sprendžia, kurią knygą skaityti vasaros metu.
B) Kai paauglys apšaukia draugą, atsisėdusį į jo vietą.
C) Kai paauglys netikėtai išgirsta stiprų garsą ir krūpteli.
D) Kai paauglys supyksta ant ant tėvų, neleidusių užsiimti ekstremaliu sportu.

E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder

E2 was diagnosed with specific learning disorders (dyslexia)

E3 both specific learning disorders (reading and writing) and an attention disorder.

Neurotypical (T)

Mažų vaikų smegenys smarkiai auga, sulaukus 6–7 metų smegenys sudaro apie 90–95 proc. suaugusiojo smegenų dydžio. Nors smegenys nustoja augti, tačiau paauglystėje vyksta intensyvus galvos smegenų persitvarkymas – nenaudojamos jungtys tarp neuronų pašalinamos, kartu sustiprėja kitos jungtys, pagerėja informacijos perdavimas tarp skirtingų smegenų centrų. Tokiu būdu smegenų veikla tampa efektyvesnė. Anksčiau neuromokslininkai teigė, kad smegenys baigia brėsti apie 20-uosius gyvenimo metus. Tobulėjant mokslinėse tyrimuose naudojamai įrangai, nustatyta, kad smegenys vystosi dar ilgai, pasibaigus paauglystei. Viena paskutinių subręsta smegenų žievės dalis kaktoje. Ji atsakinga už sąmoningą sprendimų priėmimą, savikontrolę, emocijų valdymą.
Kurioje situacijoje aktyviausiai veiks paauglio smegenų žievės dalis kaktoje?
A) Kai paauglys sprendžia, kurią knygą skaityti vasaros metu.
B) Kai paauglys apšaukia draugą, atsisėdusį į jo vietą.
C) Kai paauglys netikėtai išgirsta stiprų garsą ir krūpteli.
D) Kai paauglys supyksta ant ant tėvų, neleidusių užsiimti ekstremaliu sportu.

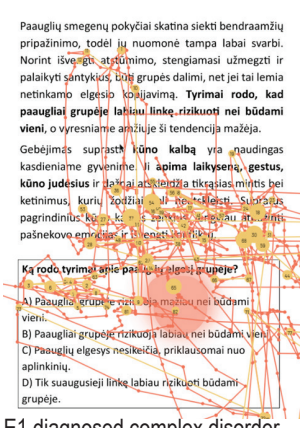
Example of the exercise

Note. Only question and answer options have changed: "In which situation is the prefrontal cortex of an adolescent most active?" Answer options: "A) When a teenager decides which book to read during summer. B) When a teenager yells at a friend who sat in their seat. C) When a teenager flinches after hearing a loud sound. D) When a teenager gets angry at parents for not allowing extreme sports."

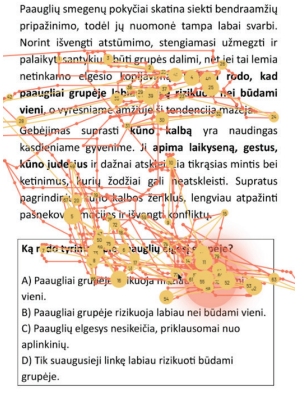
Figure 4 shows the same decorative-image condition but paired with a transfer-type question. E1's scanpath was highly disorganized, with long, erratic saccades shifting non-linearly between the question and text. The image was ignored. E2 began reading the text but quickly moved to the question area. Upon seeing the word "adolescent," E2 fixated on the boy in the image, then switched back and forth between the picture and the text – indicating an attempt to extract meaning from irrelevant content. The main text was largely overlooked. E3's scanpath involved three zones: image, text, and question. Compared to E1 and E2, E3 devoted more time to reading and analysing the question, focusing primarily on the right-hand side of the text and treating the answer options proportionally. Student T showed a structured pattern, re-reading the text and concentrating on the answer options. The image received no attention, suggesting T recognized it as irrelevant. Despite being non-informative, the decorative image drew attention from all three neurodivergent students, demonstrating the seductive details effect in learners with cognitive vulnerabilities.

Figure 5

Highlighted Text with Retention Question


Paauglių smegenų pokyčiai skatina siekti bendraamžių pripažinimo, todėl jų nuomonė tampa labai svarbi. Norint išvengti atstūmimo, stengiamasi užmegzti ir palaikyti santykius, būti grupės dalimi, net jei tai lemia netinkamo elgesio kopijavimą. **Tyrimai rodo, kad paaugliai grupėje labiau linkę rizikuoti nei būdami vieni**, o vyresniame amžiuje ši tendencija mažėja.
Gebėjimas suprasti **kūno kalbą** yra naudingas kasdieniame gyvenime. Ji **apima laikyseną, gestus, kūno judesius** ir dažnai atskleidžia tikrąsias mintis bei ketinimus, kurių žodžiai gali neatskleisti. Supratus pagrindinius kūno kalbos ženklus, lengviau atpažinti pašnekovo emocijas ir išvengti konfliktų.
Ką rodo tyrimai apie paauglių elgesį grupėje?
A) Paauglia grupėje rizikuoja mažiau nei būdami vieni.
B) Paauglia grupėje rizikuoja labiau nei būdami vieni.
C) Paauglių elgesys nesikeičia, priklausomai nuo aplinkinių.
D) Tik suaugusieji linkę labiau rizikuoti būdami grupėje.

E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder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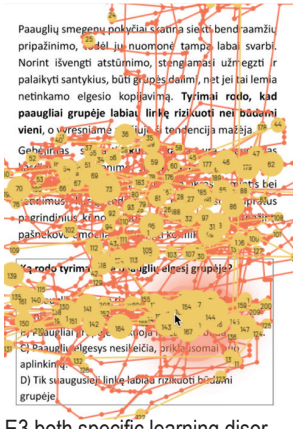
C) Paauglių elgesys nesikeičia, priklausomai nuo aplinkinių.
D) Tik suaugusieji linkę labiau rizikuoti būdami grupėje.

E2 was diagnosed with specific learning disorders (dyslexia)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Gebėjimas suprasti **kūno kalbą** yra naudingas kasdieniame gyvenime. Ji **apima laikyseną, gestus, kūno judesius** ir dažnai atskleidžia tikrąsias mintis bei ketinimus, kurių žodžiai gali neatskleisti. Supratus pagrindinius kūno kalbos ženklus, lengviau atpažinti pašnekovo emocijas ir išvengti konfliktų.
A) Paauglia grupėje rizikuoja labiau nei būdami vieni.
B) Paauglia grupėje rizikuoja labiau nei būdami vieni.
C) Paauglių elgesys nesikeičia, priklausomai nuo aplinkinių.
D) Tik suaugusieji linkę labiau rizikuoti būdami grupėje.

E3 both specific learning disorders (reading and writing) and an attention disorder.

A) Paauglia grupėje rizikuoja mažiau nei būdami vieni.
B) Paauglia grupėje rizikuoja labiau nei būdami vieni.
C) Paauglių elgesys nesikeičia, priklausomai nuo aplinkinių.
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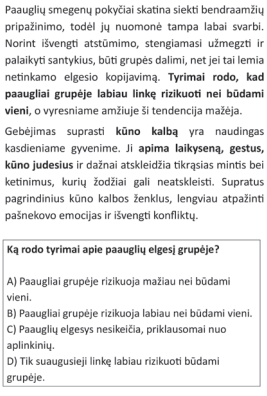
Neurotypical (T)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C) Paauglių elgesys nesikeičia, priklausomai nuo aplinkinių.
D) Tik suaugusieji linkę labiau rizikuoti būdami grupėje.

Example of the excercise

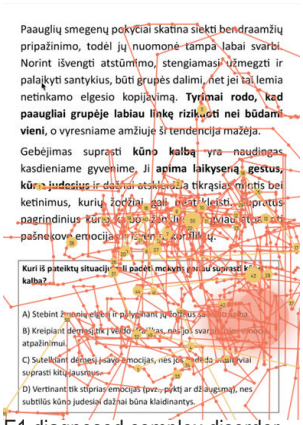
Note. The text: "Brain changes during adolescence motivate young people to seek peer approval, making their peers' opinions very important. To avoid rejection, they strive to form and maintain relationships, be part of a group, even if that means copying inappropriate behaviour. Studies show that adolescents are more likely to take risks in groups than alone, and this tendency decreases with age. The ability to understand body language – posture, gestures, and movements – is valuable in daily life. It can reveal intentions that words may not express. Recognizing these cues helps to understand others' emotions and avoid conflicts." Question and answer options: "What do studies reveal about adolescent behaviour in groups? A) Adolescents take fewer risks in groups than when alone. B) Adolescents take more risks in groups than when alone. C) Adolescent behaviour remains the same regardless of others. D) Only adults are more likely to take risks in groups."

Figure 5 presents scanpaths from the highlighted-text condition, where key segments were bolded to visually signal important content. E1's scanpath was erratic, moving in zig-zag patterns and shifting top-to-bottom and right-to-left. Numerous long saccades and regressions occurred, including returns to non-highlighted areas. E2 also exhibited zig-zag eye movements but showed clearer focus on highlighted parts. A direct scanpath from the question to the first bolded segment suggests successful use of visual cues and reduced cognitive load during reading. E3's scanpath was dense and disorganized. Many fixations clustered on the second highlighted part, although the correct answer was in the first (author's note: however, the question was answered correctly). T's scanpath was systematic, with many fixations directly on highlighted words, followed by a brief scan of the question and a chosen answer. This pattern suggests selective attention to critical content and effective use of signaling to reduce cognitive load. Overall, highlighting acted as a visual anchor for students with learning difficulties, helping reduce – though not entirely eliminate – their disorganized search behaviour seen in previous conditions.

https://doi.org/10.33225/BalticSTE/2025.158

Figure 6

Highlighted Text With Transfer Question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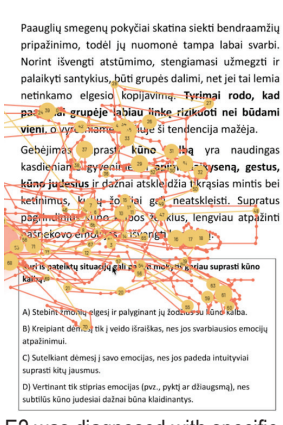
Gebėjimas suprasti kūno kalbą yra naudingas kasdieniame gyvenime. Ji apima laikyseną, gestus, kūno judesius ir dažnai atskleidžia tikrąsias mintis bei ketinimus, kurių žodžiai gali neatskleisti. Supratus pagrindinius kūno kalbos ženklus, lengviau atpažinti pašnekovo emocijas ir išvengti konfliktų.
Kuri iš pateiktų situacijų gali padėti mokytis geriau suprasti kūno kalbą?
A) Stebint žmonių elgesį ir palyginant jų žodžius su kūno kalba.
B) Kreipiant dėmesį tik į veido išraiškas, nes jos svarbiausios emocijų atpažinimui.
C) Sutelkiant dėmesį į savo emocijas, nes jos padeda intuityviai suprasti kitų jausmus.
D) Vertinant tik stiprias emocijas (pvz., pyktį ar džiaugsmą), nes subtilūs kūno judesiai dažnai būna klaidinantys.

E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder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E2 was diagnosed with specific learning disorders (dyslexia)

Paauglių smegenų pokyčiai skatina siekti bendraamžių pripažinimo, todėl jų nuomonė tampa labai svarbi. Norint išvengti atstūmimo, stengiamasi užmegzti ir palaikyti santykius, būti grupės dalimi, net jei tai lemia netinkamo elgesio kopijavimą. Tyrimai rodo, kad paauglių grupėje labiau linkę rizikuoti nei būdami vieni, o vyresniame amžiuje ši tendencija mažėja.
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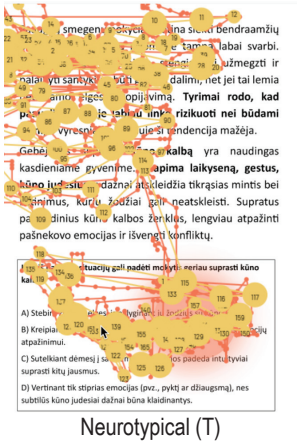
E3 both specific learning disorders (reading and writing) and an attention disorder.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C) Sutelkiant dėmesį į savo emocijas, nes jos padeda intuityviai suprasti kitų jausmus.
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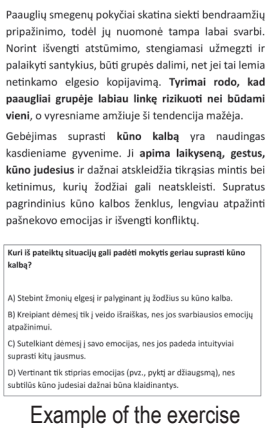
Neurotypical (T)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Kuri iš pateiktų situacijų gali padėti mokytis geriau suprasti kūno kalbą?
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D) Vertinant tik stiprias emocijas (pvz., pyktį ar džiaugsmą), nes subtilūs kūno judesiai dažnai būna klaidinantys.

Example of the exercise

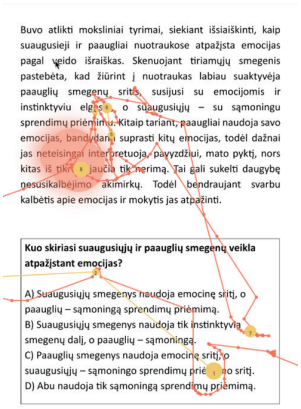
Note. Only question and answer options have changed: "Which situation could help someone learn to better understand body language? A) Observing people's behaviour and comparing it with their words. B) Focusing only on facial expressions, since they are key to emotion recognition.C) Paying attention to one's own emotions to intuitively understand others. D) Only interpreting strong emotions like anger or joy, since subtle cues can be misleading."

Figure 6 shows the scanpath in the highlighted-text condition with a transfer question. E1's scanpath remained highly disorganized and inefficient. While some fixations clustered on highlighted parts, fixation durations were short (no large dots visible), and frequent saccades moved between the question and unrelated text areas. These long, irregular saccades suggest reactive, not strategic, visual search. E2 showed more and longer fixations than E1, particularly around highlighted text. Moderate regressions and shorter saccades suggest re-reading to build inferences. Despite dyslexia, E2 used visual cues strategically, reducing search effort and supporting integrative processing. E3's scanpath showed partial guidance by the highlighted text, but also

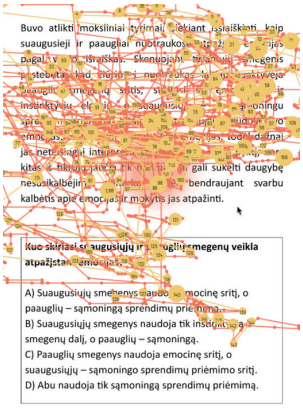
substantial disorganization. Fixations clustered in the question area, yet many saccades led to unrelated or empty regions. Highlighting drew attention but did not consistently support inference generation. In contrast, the student T displayed a clear reading sequence and focused fixations on emphasized content. T also had the longest fixation durations, proportionally distributed across the learning material.

Figure 7

Control Text Without Any Additional Enhancing Elements With Retention Question


Buvo atlikti moksliniai tyrimai, siekiant išsiaiškinti, kaip suaugusieji ir paaugliai nuotraukose atpažįsta emocijas pagal veido išraiškas. Skenuojant tiriamųjų smegenis pastebėta, kad žiūrint į nuotraukas labiau suaktyvėja paauglių smegenų sritis, susijusi su emocijomis ir instinktyviu elgesiu, o suaugusiųjų – su sąmoningu sprendimų priėmimu. Kitaip tariant, paaugliai naudoja savo emocijas, bandydami suprasti kitų emocijas, todėl dažnai jas neteisingai interpretuoja, pavyzdžiui, mato pyktį, nors kitas iš tikrųjų jaučia tik nerimą. Tai gali sukelti daugybę nesusikalbėjimo akimirkų. Todėl bendraujant svarbu kalbėtis apie emocijas ir mokytis jas atpažinti.
Kuo skiriasi suaugusiųjų ir paauglių smegenų veikla atpažįstant emocijas?
A) Suaugusiųjų smegenys naudoja emocinę sritį, o paauglių – sąmoninga sprendimų priėmimą.
B) Suaugusiųjų smegenys naudoja tik instinktyvią smegenų dalį, o paauglių – sąmoninga.
C) Paauglių smegenys naudoja emocinę sritį, o suaugusiųjų – sąmoningo sprendimų priėmimo sritį.
D) Abu naudoja tik sąmoningą sprendimų priėmimą.

E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder



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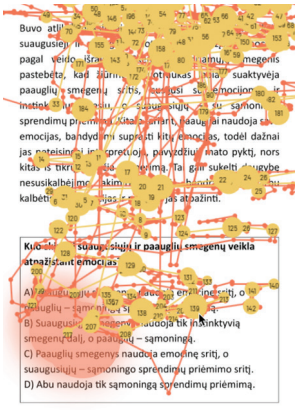
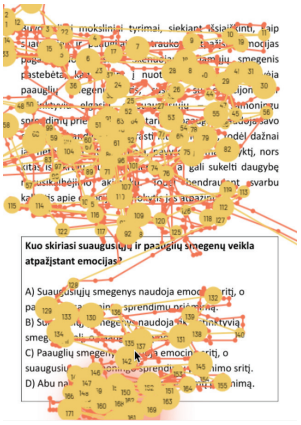
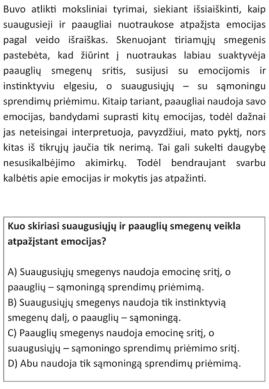


E3 both specific learning disorders (reading and writing) and an attention disorder.



Neurotypical (T)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B) Suaugusiųjų smegenys naudoja tik instinktyvią smegenų dalį, o paauglių – sąmoninga.
C) Paauglių smegenys naudoja emocinę sritį, o suaugusiųjų – sąmoningo sprendimų priėmimo sritį.
D) Abu naudoja tik sąmoningą sprendimų priėmimą.

Example of the exercise

Note. "Scientific studies have explored how adults and adolescents recognize emotions from facial expressions. Brain scans revealed that adolescents activate regions associated with emotions and instinctive behavior, while adults engage areas linked to conscious decision-making. In other words, adolescents interpret others' emotions based on their own feelings, often misjudging them—for example, seeing anger where there is actually only anxiety. This can lead to miscommunication. That's why it is important to talk about emotions and learn to recognize them." Question and answer options: "How does brain activity differ between adults and adolescents when recognizing emotions? A) Adults use emotional brain areas; adolescents use decision-making areas. B) Adults rely on instinctive brain parts; adolescents rely on conscious thought. C) Adolescents use emotional brain areas; adults use decision-making regions. D) Both rely solely on conscious decision-making."

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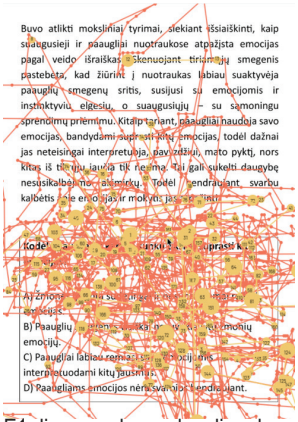
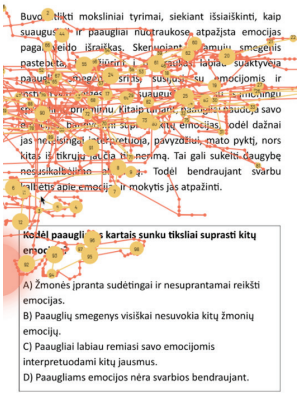
Figure 7 presents the scanpath from the control condition, where only plain text was provided with a recall question below. This served as a baseline for comparing reading strategies. E1's scanpath was highly scattered, with few short fixations and long saccades across the text and question area. E2 showed a relatively linear, methodical reading pattern not observed in previous conditions. Fixations were moderately dense, spread across the text, with short, local regressions typical of dyslexic reading. Saccades were short, and the gaze moved to the question after reading nearly the entire text. A single revisit (fixation number 149) suggests confident recall from working memory. E3's scanpath showed longer fixation durations clustered near the question and upper-middle text. Reading likely started mid-text, and transitions between clusters were poorly aligned with content relevance. While the question was visited multiple times, return paths lacked precision, indicating ineffective navigation and integration. T demonstrated a structured, low-effort reading pattern, with consistent top-to-bottom scanning and minimal regressions. Uniform fixation sizes suggest fluent decoding and low cognitive load. No regressions occurred after reading the question, indicating high recall accuracy.

Figure 8

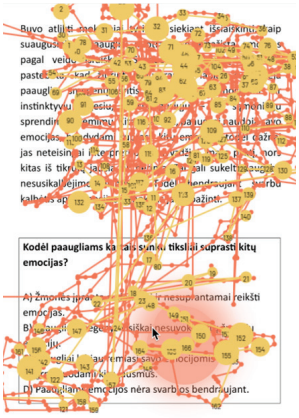
Control Text Without Any Additional Enhancing Elements with Retention Question



E1 diagnosed complex disorder involving specific learning disorders (reading and writing) and an attention disorder

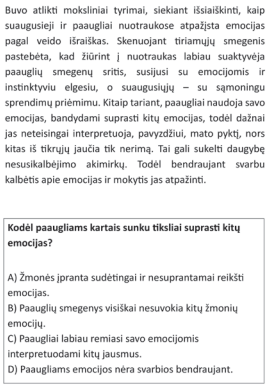


E2 was diagnosed with specific learning disorders (dyslexia)



E3 both specific learning disorders (reading and writing) and an attention disorder.

Neurotypical (T)



Example of the exercise

Note. Only question and answer options have changed: "Why is it sometimes difficult for adolescents to accurately recognize others' emotions? A) People express emotions in complex and unclear ways. B) Adolescents' brains cannot comprehend others' emotions. C) Adolescents rely more on their own emotions when interpreting others' feelings. D) Emotions are not important for adolescents in communication."

Figure 8 presents the scanpath from the control condition with a transfer question. E1's scanpath was extremely chaotic, with short, dense fixations concentrated near the lower text and question area. Saccades were long and multidirectional. Although the question attracted repeated attention, regressions to the text were unfocused and not task-driven. E2 showed sustained effort with a relatively linear reading pattern. After reading the question, E2 attempted to return to the relevant text areas, but the paths lacked precision. E3 reread the same text shortly after answering the recall question. Fixations were evenly distributed across the text and question area. Vertical saccades between both zones indicated a bidirectional search strategy. T briefly scanned the text, then focused almost entirely on the question area. Fixations were uniform in duration, and linear saccades suggested quick scanning of answer options. This focused gaze pattern reflects effective integration of information from working memory.

Discussion

This study examined how students with specific learning and attention disorders engage with science texts presented under different instructional enhancement conditions using eye-tracking data. The scanpath analysis uncovered distinct differences in reading strategies between neurodivergent (E1, E2, E3) and neurotypical student (T), as well as important insights into how instructional enhancements – such as highlighting and visual cues – modulate cognitive load and support reading strategies.

Participants diagnosed with both reading-writing disorders and attention deficits (E1 and E3) consistently exhibited fragmented, irregular scanpaths across all conditions, characterized by long, disorganized saccades and frequent regressions. These patterns suggest difficulty in sustaining attention and integrating information during reading, particularly under high cognitive load. Such findings align with Nagarajan et al. (2023) who emphasized that impaired executive function in readers with attentional disorders leads to disrupted scanpath and diminished inferential reasoning. E1's behaviour, especially in control, picture and infographic tasks, showed significant attentional capture by irrelevant elements (e.g., white space, decorative visuals), reflecting heightened vulnerability to extraneous cognitive load (Sweller, 2024).

In contrast, E2, diagnosed with specific learning disorders (dyslexia), displayed more focused, linear reading patterns. While decoding difficulties were evident in the form of short, frequent regression, E2 engaged with the tasks in a methodical way, particularly when visual cues (highlighted text) or only plain text were provided. These findings suggest that students with dyslexia may benefit from enhanced instructional scaffolding that reduces visual search demands and narrows attentional focus to key information (Parshina et al., 2022). In the absence of such scaffolds, E1's and E3's reading became less efficient, although student E2's reading pattern was the most organised in the plain text condition.

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Highlighted text consistently emerged as the most beneficial support for both E2 and E3. The visual signaling reduced wandering gaze behaviour and supported more accurate task-related regressions – in line with the signaling principle from multimedia learning theory (Mayer, 2024). E3, despite attentional impairments, exhibited notably improved fixation patterns when highlights were present, indicating that visual salience can partially offset deficits in top-down control (Coskun & Cagiltay, 2022). However, infographics and decorative pictures introduced mixed effects: while they did not distract the neurotypical student's visual attention, these visual elements distracted neurodivergent students and introduced extraneous load (Ma et al., 2022).

Neurotypical performance across all conditions was marked by short fixation durations, minimal regressions, and strategic re-reading. This participant consistently re-engaged only the relevant parts of the text post-question, exemplifying adaptive reading and comprehension strategies (Richter & Scheiter, 2019). The comparative efficiency of neurotypical scanpath highlights the gap in visual self-regulation skills among students with learning difficulties and underscores the need for educational design to mitigate this disparity.

Overall, this study reinforces the value of eye-tracking for diagnosing cognitive challenges and supports the integration of signaling and visual minimization strategies in science education for students with reading and attention disorders. Future research should explore adaptive learning environments that respond dynamically to students' visual behaviour, promoting more equitable access to scientific content and deeper learning.

Conclusions and Implications

This study looked into how students with specific learning and attention disorders (dyslexia and attention deficit, ADHD) process science texts under different instructional conditions, with a focus on seductive details and visual enhancements. Eye-tracking analysis revealed that neurodivergent students exhibited more disorganized scanpaths, longer saccades, and frequent regressions compared to the neurotypical student. Students with both dyslexia and attention deficits showed the most fragmented reading behaviour, while the student with dyslexia alone demonstrated more structured gaze patterns, especially in the plain and highlighted text conditions.

Seductive details, such as decorative images, consistently distracted neurodivergent students and increased extraneous cognitive load. These visuals drew attention away from the main text, particularly during tasks requiring inference. In contrast, highlighted text supported more focused reading and task-relevant regressions, though it did not entirely eliminate disorganized search behaviour.

The results support the use of signaling and visual simplification in science education for students with cognitive difficulties. Eye-tracking proved to be an effective method for revealing how these learners engage with texts. Future instructional designs should avoid unnecessary visual stimuli and emphasize clarity and relevance to better support reading comprehension and reduce cognitive strain.

This case study demonstrated that instructional design elements – such as text highlighting and decorative images – affect students with learning and attention disorders (dyslexia and attention deficit or ADHD) differently than neurotypical student.

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Eye-tracking data revealed that seductive details, including irrelevant images, frequently disrupted attention and increased cognitive load for neurodivergent students, while neurotypical students remained unaffected. In contrast, visual signaling through text highlighting partially supported more focused reading and helped guide attention toward relevant information. However, these supports did not fully compensate for disorganized scanpaths in students with combined attention and learning difficulties. These findings highlight the importance of minimizing unnecessary visual complexity and prioritizing clarity and relevance in instructional materials for cognitively vulnerable learners. Practically, the results suggest that science education content should avoid seductive details and instead incorporate targeted visual scaffolds that reduce search effort and cognitive strain. More broadly, this research supports principles of Universal Design for Learning (UDL) and demonstrates the value of eye-tracking as a tool to inform adaptive educational interventions. Future digital learning environments should aim to detect and respond to learners' attentional patterns in real time, promoting equitable access to academic content for all students.

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GENERATING CURRICULA: A HUMAN-CENTRED PERSPECTIVE IN THE ERA OF ARTIFICIAL INTELLIGENCE

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Abstract

This study explores generative mechanisms of curriculum design from a human-centred perspective, with a focus on the integration of Artificial Intelligence (AI) into engineering education. As curricula evolve to meet the demands of a technologically advanced and globally connected society, it is crucial to preserve the educational values rooted in human agency, cultural context, and pedagogical reasoning. The research aimed to investigate how traditional curriculum development processes can be enhanced through AI tools while preserving the essential role of human educators. A mixed-method approach was used, combining quantitative Likert-scale surveys and qualitative open-ended responses from 43 participants involved in curriculum development and implementation across higher and vocational education and industry. The results show that AI is perceived as highly effective in automating administrative tasks and personalizing learning, but concerns remain about ethical issues, data privacy, and potential marginalization of human educators. Most respondents emphasized that AI should serve as a supportive tool rather than a replacement. The findings underscore the importance of hybrid curriculum models that integrate AI for operational efficiency while maintaining human agency in decision-making, pedagogy, and ethical oversight. The study offers practical implications for future curriculum reforms and teacher training in an AI-enhanced educational landscape.

Keywords: *Curriculum Development, Artificial Intelligence in Education, Human-Centred Learning, Engineering Education, Generative Mechanism of Curricula.*

Introduction

Estonian scientist and zoologist Aleksey Turovsky has noted that no child or animal can survive without learning. Learning is a fundamental human intellectual activity, rooted in experience and aimed at acquiring new knowledge and skills, experiences, and behaviour. It may arise spontaneously through everyday encounters or be carefully planned and structured within educational systems. This duality between spontaneous and planned learning forms the background against which any curriculum–the formal plan for learning–evolves.

However, it is essential to recognize that learning is not only an individual process. As Paulo Freire (2018) has highlighted, education is also a social act, influenced by cultural and political contexts. The curriculum serves not only as a tool for individual

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development but also as a mechanism through which societies establish values, norms, culture, and ideologies for future generations.

Higher education, which should train specialists for different areas of life, needs a rationally organized starting point - general education. This is specific to each society, which presumes somewhat different selection of the learning content (in the humanities) and a common part, as STEM (Science, Technology, Engineering, and Mathematics) is global and almost similar everywhere.

The higher the educational level a learner reaches, the greater the role of field-specific knowledge becomes. Also, in the term "know-how" of knowledge-based skills, the word "know" comes first, and specialist knowledge is inevitably international, because of technologies. All skills are based on knowledge. The question is mostly where this knowledge can be applied and whether there are relevant resources or not. Due to the lack of appropriate environments, not all kinds of specialists can be trained in some countries.

Learning takes place across diverse contexts–from homes to higher education institutions–being influenced by the learners' age, environment, and personal capabilities. Historical precedents, such as Goethe's travels to Italy or British educational tours across Europe, exemplify the long-standing tradition of experiential learning.

The importance of context in learning is highlighted by Lev Vygotsky (1978), who emphasized the role of social interaction in cognitive development. The Zone of Proximal Development (ZPD) concept suggests that learners progress when guided by more knowledgeable persons - whether peers, mentors, or teachers. Thus, educational environments should be seen not only as places for individual learning but also as collaborative spaces that encourage sharing of knowledge and experiences.

The present study examined the evolving role of Artificial Intelligence (AI) in the process of curriculum development, alongside the traditional human-driven processes, to better understand how these two forces can be united to enhance educational practice. The aim of this study was to explore the mechanisms of curriculum development in the context of engineering education, with a specific focus on the possibilities of integration of AI and its influences.

Curriculum as a Structured Whole

Curricula are structured documents that usually present educational aims, content, expected outcomes, and assessment methods, providing a roadmap for organizing learning at various stages of education. However, these documents are not static. According to William Pinar (2012), curriculum development remains a "complicated conversation" within the society, where social groups negotiate what is considered worth learning, typically following the cycles of every 10 years.

Curriculum development employs various verbs such as "design," "compile," or "write," each emphasizing different aspects of this process. The outcome is more than a document–it is a social and cultural contract and intellectual artifact. Curriculum, as a product of negotiations, consensus, and agreement, is deeply interwoven with political and social ideologies. It can both reflect and reinforce existing national power structures, as discussed by Michael Apple (2004) in his work on the "hidden curriculum."

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The concept of "hidden curriculum" created by Philip Wesley Jackson (1968) explores how education systems transmit implicit values that shape students' identities, behaviours, and social roles. This hidden curriculum often reflects societal hierarchies and inequalities, such as class, race, and gender, which may not be openly acknowledged, but are nonetheless deeply native within educational practices.

Curricula not only prescribe what must be learned (explicit curricula) but also imply social values and norms (implicit curriculum) and omit certain content (null curriculum). Several scholars have explored these layers, noting that neglecting the hidden curriculum renders teaching and learning insignificant. As Ted Aoki (1986) argued, a tension between the curriculum as planned and the curriculum as it exists—a duality essential to understanding educational experiences.

In Nordic contexts, especially Finland, curriculum development reflects a philosophical commitment to *Bildung*—the holistic development of individuals. According to Tero Autio (2022), curricula of comprehensive schools serve as the intellectual centrepieces of society. Finnish educational culture prioritizes adequacy over excellence, recognizing the societal value of vocational education alongside academic routes. Such a balanced approach has contributed to a more equitable education system.

Moreover, the concept of *Bildung* is rooted in the German educational tradition, which emphasizes personal growth and the development of critical thinking skills. This approach is aligned with John Dewey's (1938) philosophy of education, where learning is seen as a continuous process of adapting to one's environment and engaging in reflective thinking. By valuing both academic and vocational education, Finland has achieved a more inclusive and adaptable system serving the needs of its citizens and workforce (Autio, 2022).

Curricula are expected to be focused, well organized, effectively developed, concise, and appropriate for implementation at schools and universities. Curricula are governing documents for organizing learning at different levels, which must be followed according to the standards set by laws and strategic priorities. They are expected to be clear in style, readable, and free from gender, political or religious bias (Läänemets, 2012).

The social role and ideological purpose of education have been the focus of many scholars. Michael Apple (2004) discusses the curriculum as an ideological mechanism in his work "Ideology and Curriculum", noting that curricula not only promote knowledge acquisition but also advocate for certain societal orders and power structures. According to Apple, while education systems are formal, they can reflect and reinforce certain ideological and political interests.

Curriculum development is an ongoing process that requires regular evaluation of current processes in socio-political tendencies of globalization and technological developments. It is of utmost importance to identify outdated content and address potential gaps in existing curriculum documents to ensure their alignment with evolving needs in a particular field of education. Issues of educational economics must be planned and assessed in advance.

Designing and implementing curricula based on different models requires resources, teacher training, and instructional materials. The success of such implementation depends on the systematic support provided. Educational systems must also be flexible enough to adapt curricula to local contexts and changing societal needs, which may not always

https://doi.org/10.33225/BalticSTE/2025.180

align with predefined models. Several models have been developed to systematize curriculum design, including:

- Wheeler's Model (1967): a five-stage cyclic model emphasizing integration and evaluation.
- Tyler's Model (1969): focuses on defining objectives, aligning content, and evaluation.
- Taba's Model (1962): advocates for "grassroots" curriculum development by teachers.
- Goodlad's Model (1988): includes values, conventional wisdom, and learner needs.
- Kerr's Model (1972): structures learning around objectives, content, experiences, and evaluation.
- Model by Urve Läänemets (2012) (see Figure 1) includes the following steps: "Why?" - formulation of objectives, set according to the scope of the planned process. "How much?" - study time as a resource for achieving balance between time allocated for study and the amount and complexity of the chosen learning content. "When?" - supports determination sequence of learning activities and rational integration of an interdisciplinary approach, learning content, and learning experiences. "What?"- defines the content of learning recognized and valued in a specific society and culture, to shape opportunities for continuing education. "Where?" - how to create a supportive environment for subject-specific learning or integrated learning activities (e.g., projects, challenges, etc.). "Who?" concerns teachers and students participating in the learning process, preliminary knowledge of the students, and the availability of the learning materials considered. "How?" - choices of learning and teaching methods and learning forms for learning with understanding.
- Psycho-Didactical Model of Engineering Pedagogy, designed by Adolf Melezinek (1999) and developed by Tiia Rüütmann (2023) is an iterative process for design of a curriculum or syllabus, starting from design of learning goals and outcomes and ends with reflection and analysis of students' feedback for the purpose of further improvement and ensuring constructive alignment (see Figure 2).

In engineering education, the integration of Problem-Based Learning (PBL) and Project-Based Learning (PjBL), within the framework of the CDIO (Conceive, Design, Implement, Operate) as a foundation for developing a curriculum aligns both industry needs and academic rigor (Crawley et al, 2014). These methodologies, when balanced with discipline-based learning, foster an environment, where students can acquire both theoretical knowledge and skills for solving real world problems. Discipline-based learning provides systematic knowledge and abstract thinking, while PBL and PjBL provide analytical and critical thinking. According to Crawley (2014), a balance must be created between discipline-based learning, PBL, and PjBL.

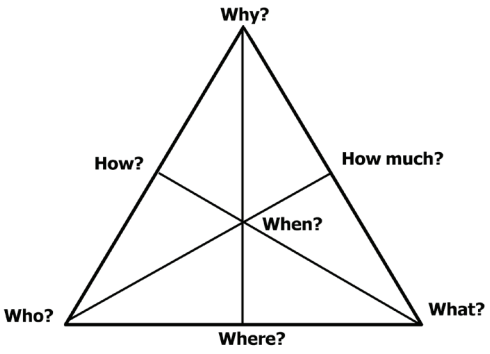
To successfully integrate above introduced pedagogical approaches, it is critical to ensure that the curriculum is coherently designed and that there is constructive alignment between learning outcomes, learners' prerequisites, course content, teaching methods, and assessment strategies. In this context, the curriculum should promote the acquisition

https://doi.org/10.33225/BalticSTE/2025.180

of both theoretical knowledge and practical skills, ensuring that students are prepared for the realities of the professional world. The design of the curriculum must also ensure that learning is progressing using earlier courses, building the foundational knowledge and skills necessary for later, more complex study tasks.

Figure 1

Model for Curriculum Design by Läänemets (2012)



Blatchford and Chen (2020) discuss the integration of AI into curriculum design, exploring the balance between technological innovation and the need for a human-centred approach. AI is becoming a valuable tool for tracking student progress, providing real-time feedback, and creating adaptive learning environments considering learners' needs. Implementation of AI must be carried out cautiously, ensuring that it complements human interaction rather than replaces it.

In the 21st century, technology and AI introduce new dimensions to curriculum development. While offering potential benefits such as adaptive learning systems and predictive analytics, AI also raises concerns about control, bias, and misuse (Kim 2022). Societal readiness, legal frameworks, and ethical considerations must guide AI integration in education. Technology and AI have transformed not only the ways in which learning occurs but also the methods by which curricula are designed and implemented. These technologies raise questions regarding data privacy, security, and algorithmic bias (Kim 2022).

A significant challenge in AI-driven curriculum development lies in addressing potential biases embedded in algorithms. As algorithms are created by humans, they can unintentionally reflect societal biases. This concern was raised by O'Neil (2016) in "Weapons of Math Destruction", where the author argues that biased algorithms can perpetuate existing inequalities in education and other sectors. Thus, while AI offers great potential for personalized learning, it must be implemented within an ethical framework that ensures fairness and inclusivity.

In Estonia, for example, curriculum development has been criticized as ineffective over the past 35 years, hindered by pseudo-democracy and lack of professional leadership. Recognizing such challenges is crucial for initiating meaningful reform. As noted at the World Education Forum in London (2020), curriculum reform should begin as early as kindergarten.

https://doi.org/10.33225/BalticSTE/2025.180

Figure 2
Psycho-Didactical Model of Engineering Pedagogy

The relationship between learning and education has always been at the core of both theoretical and practical discussions. While traditional curricula have often focused on the transfer of knowledge and theory, in recent decades, emphasis has shifted toward the experiential and critical aspects of learning, as developed by theorists such as John Dewey. Dewey (1938) emphasized that education should not be merely about knowledge transmission, but also a social and reflective process that integrates personal experience with broader awareness, preparing students for adulthood. These ideas had a profound impact on educational theory in the middle of the 20th century, as they helped to shape the humanistic and life-practice orientation of curricula.

Curriculum development, as highlighted by Tero Autio (2022), should not be viewed merely as an organizational structure but also as a means through which society channels the youth and shapes their worldviews, providing carefully selected knowledge for the upcoming generation.

International organizations have played a central role in setting educational standards and promoting a shift from traditional rote learning to competency-based education. The OECD's *Education 2030* framework emphasizes the importance of learning to learn, critical thinking, and collaborative problem-solving as key competencies for future generations. In this context, curriculum development is expected to go beyond content delivery to focus on skills-building, adaptability, and lifelong learning.

Generative Mechanisms for Developing Curricula

The generative mechanism of curriculum and syllabi development includes several elements, which allow for planning relevant, structured activities in this process. Prior data and experience concerning analysis and evaluation, implementation and monitoring, implementing curriculum theories, educational philosophical approaches, and the role of educational policy, as well as curriculum design models and strategies, taking account of

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the nature of learning, have to be studied in-depth**.** It is necessary to consider the current system of education, as well as that designed for future, as a meaningful whole starting from kindergarten and ending up with doctoral studies.

Understandably, educators have started to use generative AI to create personalized and adaptable pathways for student learning. The integrative potential of AI has enabled students to generate their own information, which enhances the retrieval and application of the content learned (Wilson & Bauer, 2024). According to Hand et al. (2021), new national curricula emphasize knowledge generation approaches, focusing on learning practices and generative tools. This has been shown to significantly improve students' content knowledge, critical thinking, and other competencies.

Generative AI can also support teachers' lesson planning by efficiently creating and refining lesson outlines (Powell & Courchesne, 2024). Generative methods are used to develop interactive educational software by promoting explorative learning models. These methods offer high reusability and cost reduction, making them valuable for creating novel learning models.

Advanced models like GPT-3, GPT-4 and Generative Adversarial Networks (GANs) play a central role in generating personalized and adaptable educational content, helping to create virtual laboratories and simulations, enhancing hands-on learning experiences (Wilson & Bauer, 2024; Tariq, 2004). Generative AI has been found to significantly enhance teaching performance by improving ease of use, thereby impacting student-focused learning, learning material development, and teaching practice enhancement (Mulyani et al, 2025). The use of generative learning environments has a positive impact on students' critical thinking skills, science conceptual understanding, language skills, students' learning achievement and learning motivation, including varying impacts on physical, socio-emotional, and intellectual outcomes (Zhu et al, 2025; Liu et al, 2025).

Challenges in implementing generative curriculum design include technical limitations, the necessary teacher training, adaptability, privacy concerns, and ethical issues (Gupta, 2024). Traditional assessment methods in higher education may not operate effectively anymore in the Generative AI era, and there is a need for innovative and refocused teaching and assessment strategies to assess student learning with deep understanding (Gupta, 2024).

Educators and educational researchers should design learning environments that empower students to have ownership in constructing their views of generative AI as future engineers. It can provide professional development, clear guidelines, and access to AI software and technical support to motivate Generative AI integration in education (Xu et al, 2024; Davy et al, 2025).

Effective use of Generative AI in education requires comprehensive teacher training programs, which should focus on developing AI literacy among educators and equipping them with the skills to integrate new tools into their teaching strategies (Yin et al, 2025).

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Research Methodology

General Background

The research methodology employed in this study adopts a mixed-methods approach to explore the integration of Artificial Intelligence (AI) into curriculum development from a human-centred perspective. The study focuses on engineering education and involves 43 participants, including program directors, faculty, vocational teachers, and industry representatives, ensuring a comprehensive multi-stakeholder perspective. The theoretical framework draws on curriculum design models (e.g., Läänemets, 2012; Melezinek, 1999) and emphasizes the importance of human agency, ethical oversight, and hybrid learning models. The research design is purposive, targeting individuals with direct experience in curriculum development, and the scope encompasses higher and vocational education, reflecting contemporary challenges and opportunities in AI-enhanced education.

Sample

This study employed a purposive sampling strategy, targeting individuals with direct experience in curriculum development or implementation in engineering education. The sample comprised a diverse group of stakeholders representing both academic and industry perspectives, including:

- Program directors (curriculum coordinators) from engineering faculties at universities and higher education institutions, responsible for program design and development (n=7).
- Engineering faculty and lecturers engaged in teaching and implementing curricular frameworks into instructional practice (n=11).
- Teachers at vocational schools delivering applied technical education relevant to the engineering domain (n=19).
- Employers or industry representatives contributing to the specification of training needs and offering insights into labour market expectations and technological trends (n=6).

This multi-stakeholder composition of the sample, including 43 participants, ensured a comprehensive understanding of curriculum needs and challenges across educational levels and institutional contexts in engineering education.

Instrument and Procedures

A mixed methods' approach was employed, combining both qualitative and quantitative research techniques to gather comprehensive data on the participants' experiences and perceptions.

Qualitative aspect of the research involved 24 open-ended questions where participants could express their views on the role of human agency and AI in curriculum development.

https://doi.org/10.33225/BalticSTE/2025.180

The following themes were explored in the qualitative analysis:

- General attitudes towards curriculum development.
- AI in education.
- Human vs. AI influence.
- Skills and competencies for the future.
- Ethical concerns and data privacy

A questionnaire with 6-point Likert-scale response options was used in the quantitative study for identification of key trends in participants' perceptions on generative mechanism of curriculum and role of AI in this process. 21 questions were presented as statements, a response scale used had options from "0 – absolutely do not agree" up to "5 – fully agree". After each statement, it was also possible to leave a comment and explain the answer.

The following quantitative analysis of outcomes focuses on the proportion of respondents who expressed their agreement with the statements by selecting the upper two points on the Likert scale, specifically "agree" and "fully agree", which are interpreted as indicative of positive endorsement of the statements.

Data Analysis

The study employed a dual approach to data analysis, aligning with its mixed-methods design. Quantitative data from the Likert-scale survey (21 items, scored 0–5) were analysed descriptively, focusing on the proportion of respondents who selected the upper two agreement levels ("agree" and "fully agree") to identify trends in perceptions of AI's role in curriculum development. Percentages were calculated to highlight consensus areas, such as AI's effectiveness in personalization (77%) or concerns about data privacy (83%).

Qualitative data from 24 open-ended responses were thematically analysed to explore nuanced perspectives. Responses were coded into five pre-defined themes (e.g., ethical concerns, human-AI balance) using an inductive approach, with representative quotes extracted to illustrate key findings. Triangulation of quantitative and qualitative results enriched interpretations, revealing tensions between AI's efficiency and the irreplaceable role of human educators.

Research Results

This study aimed to identify how AI could contribute to more effective and personalized learning while highlighting the essential human aspects of curriculum development.

Results of quantitative research presented respondents' positive attitudes related to AI including its ability to offer personalized feedback (77% of respondents agreed and fully agreed), track student progress in real-time (37%), offer the support of a virtual assistant (78%), and provide efficient content delivery (e.g. in form of a chatbot 61%).

Negative concerns focused on the perceived risks of dehumanizing education, such as a decrease in face-to-face interaction and collaboration (79%), concerns about data privacy (83%), and the potential for AI to reinforce existing biases (48%).

https://doi.org/10.33225/BalticSTE/2025.180

Participants emphasized the need for human educators to maintain a central role in guiding students' ethical, social, and emotional development, suggesting that AI should complement human instruction rather than replace it (91%). This highlights the ongoing concern that AI should reinforce the importance of human involvement in education.

Participants were asked to rate the effectiveness of AI in various aspects of curriculum development. Most respondents (77%) agreed that AI is effective for enhancing personalized learning. This indicates strong support for AI's potential when offering tailored educational paths for students. Respondents viewed AI as very effective in automating administrative tasks such as lesson planning (68%), grading and scheduling (72%). This suggests that educators and instructional designers see significant potential in AI to reduce their administrative burden, allowing them to focus on more interactive aspects of teaching. Approximately 74% of participants rated AI as an effective tool in helping to improve curriculum design by suggesting suitable content, which aligns with the idea that AI can assist in organizing and structuring learning material, potentially saving educators time and effort in the planning process. Respondents also pointed out that AI could assist in analysing professional standards (61%), and educational and social demand for relevant education and speciality (53%) in the process of curriculum design.

Most widely used AI tools in curriculum development according to the respondents' experience were: ChatGPT4 (85%), MS Copilot (65%), Claude (56%), Notion AI (35%), Google Notebook LM (32%), DeepSeek (24%).

Participants were asked to rate criteria that could describe the ideal generative mechanism in curricula design where human-centred and AI-supported perspectives are balanced. The following characteristics were pointed out (see Figure 3). As can be seen, the highest value had professional standards and other official regulations (97%). Three criteria (learning content, learning goals, and outcomes meeting educational and social demands) were rated by 85% of respondents, and 84% pointed out the importance of balancing PBL and subject-based learning. 80% of respondents valued the importance of selection of relevant teaching methodology, and 79%, the importance of assessment methodology in the AI era. 71% of respondents valued pedagogical basis and theories as the foundation for curriculum design. Learners' initial level/prerequisites, a safe and supportive learning environment, and admission requirements were valued by 68% of respondents. The lowest rating had the following criteria: constructive alignment (59%), faculty recruitment (52%), structure and modulation (57%), and new technology in the classroom (55%).

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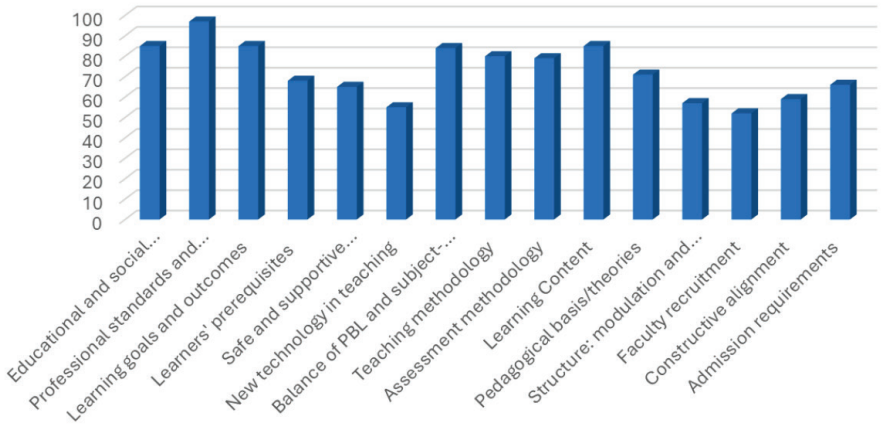
Figure 3

Criteria of Human-Centred and AI-Supported Generative Mechanism for Curricula



The qualitative data was collected from 24 open-ended questions in the survey, where participants expressed their thoughts on AI's role in curriculum development, the challenges it presents, and its benefits. The responses were categorized into the following key themes:

- General attitudes towards curriculum development: questions assessed how participants perceive the importance of curriculum design, the factors influencing its development, and the role of educational institutions in shaping curricula. A participant wrote: *"Curriculum design is not just a technical task; it reflects the broader values and goals of an education system. I believe that without a clear philosophical foundation and collaboration among stakeholders, curriculum reforms risk being superficial or short-lived."*
- AI in education: questions explored the extent to which participants believed AI could support curriculum development, including automation of certain aspects and activities, enhancement of personalized learning experiences, and integration of technology in the learning process. A participant answered*: "AI has the potential to significantly streamline certain curriculum-related tasks, such as aligning learning outcomes with assessments or identifying content gaps. However, its effectiveness depends on how well it is integrated into existing pedagogical frameworks."*
- Human vs. AI influence: a key part of the questionnaire focused on balancing the human and technological influences in curriculum development, probing whether participants felt that AI could replace human agency, or if it should complement the educational process. A participant noted: *"While AI tools can support educators by handling repetitive tasks or data analysis, the human element remains indispensable. Curriculum development involves informed human judgment, cultural sensitivity, and pedagogical intuition—qualities that AI cannot replicate."*
- Skills and competencies for the future: questions explored the competencies that participants believed should be emphasized in the curriculum, including

soft skills (e.g., critical thinking, collaboration) and technical skills (e.g., programming, data science). A participant responded: *"We talk a lot about digital skills, but soft skills are often underestimated. In a rapidly changing world, critical thinking and collaboration are not just 'nice to have'—they are essential for navigating complexity and ambiguity in the framework of speciality studies. But professional competencies remain more important than ever, of course."*

- Ethical concerns and data privacy: A recurring concern among respondents was the ethical implications of AI, particularly around issues such as data privacy, surveillance, and the potential for bias in AI algorithms. One respondent stated: *"One of my main concerns with integrating AI into education is the lack of transparency around how data is collected, stored, and used. Without safeguards and ethical norms, there's a real risk of violating students' and faculty's privacy and undermining trust in educational institutions."*

These findings help to guide future curriculum development policies and practices, especially in engineering education, where the integration of AI tools in teaching and learning environments is becoming increasingly important. Moreover, this research contributes to the ongoing discourse on the balance between human agency and technological advancement in educational systems.

Discussion

Integration of AI into curriculum development brings both potential benefits and challenges. The quantitative analysis suggests that while there is general optimism about AI's capacity to personalize learning, respondents express reservations about its role in replacing human involvement in education. The qualitative analysis provides deeper insights into these reservations, with participants voicing concerns about the loss of human touch in learning experiences and the ethical implications of AI decision-making.

A central theme that emerged, considering both the quantitative and qualitative data, is the concern about AI replacing human educators. While AI can enhance efficiency, participants emphasized that human teachers are crucial for fostering critical thinking, creativity, and emotional intelligence. Despite the efficiency AI offers in terms of data handling and content delivery, the need for human interaction and guidance was repeatedly emphasized. This finding adds a new dimension to the ongoing debate on the role of AI in education, reinforcing that AI should serve as a complementary tool, not a replacement for teachers. One respondent wrote*: "There is a risk that increasing AI involvement might marginalize educators' professional expertise, but also cultural dimensions of education. I believe AI should serve as an assistant rather than a substitute, preserving the educator's role as a critical decision-maker in curriculum design."* The findings suggest that while AI holds a significant potential to enhance various aspects of curriculum development, there remains a strong emphasis on preserving the role of human educators in the process.

Ethical considerations surrounding AI's use in education were also commonly raised by respondents. Universities must establish ethical guidelines for the integration of AI in education, focusing on transparency, fairness, and data privacy to ensure that AI

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systems are used with responsibility. Educators should receive continuous professional guidance on how to effectively incorporate AI into their teaching practices, ensuring that they can leverage the technology, while maintaining control over the learning environment. One consideration of a respondent*: "It is essential that educational institutions take a proactive role in developing ethical frameworks for AI use. Without clear guidelines on transparency, responsibility, fairness, and data protection, we risk deploying technologies that may unintentionally harm learners."*

The quantitative data shows overwhelming agreement on the effectiveness of AI in personalizing learning experiences. This aligns with the qualitative responses, where participants highlighted AI's ability to cater to diverse learning needs. However, a balanced approach is essential, ensuring that AI-driven personalization does not undermine the importance of human judgment and emotional support. A respondent said: *"AI can tailor the curriculum to the individual needs of students, adapting to their pace and learning style. This could greatly benefit diverse student populations with varying levels of competence and readiness. But students also need to learn how to use wisely the new technology, including AI"*

Both the quantitative and qualitative findings emphasize the role of AI in automating administrative tasks. This support suggests that educators appreciate AI's capacity to reduce workload, thus allowing them to focus on more meaningful interactions with students. However, concerns about technology dependency and its integration into educational practices remain. One responder stressed: *"The curriculum may be created by an interdisciplinary team, where AI helps to process information and find the focus, but the final decisions must be made by a human".*

This study also contributed new insights into the potential for hybrid models of education that combine the strengths of both AI and human educators. Participants emphasized the importance of finding a balance between technological tools and human involvement in creating a well-rounded learning experience. It also aligns with the growing interest in hybrid models where AI can be used for tasks such as personalized content delivery, while educators focus on fostering social-emotional development, critical thinking, and providing support tailored to students' needs. This hybrid approach offers a practical model for the future of education, wherein AI serves to enhance, not overshadow, the human element. One respondent wrote: *"I see real value in a hybrid educational model where AI handles data-driven personalization and administrative tasks, allowing educators to concentrate on what machines cannot do—mentoring, motivating, and responding to students' emotional and cognitive needs in real time."*

Development of curricula should follow a systematic, iterative, cyclic process that involves defining educational objectives, identifying the necessary content, selecting appropriate teaching methods, and continuously refining the curriculum based on feedback from various stakeholders.

Generative mechanisms of curricula design are presented in Figure 4, designed according to the respondents' viewpoints in the present study. According to Figure 4, curriculum design depends on the input from international developments, resources, strategic needs, and short-term needs to design relevant aims, content, environment, and achieve recognition.

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Figure 4
Generative Mechanism of Curriculum Development Designed Based on the Present Study

Integration of AI into curriculum development is a transformative process that requires careful planning, ethical consideration, and collaboration. Findings from this study provide a foundation for future research and practical applications, emphasizing the need for a balanced approach that preserves the human element of education while harnessing the capabilities of AI. By following the outlined future steps, educational institutions can ensure that AI enhances, rather than replaces, the rich and multifaceted process of teaching and learning.

Conclusions and Implications

Curriculum development remains a dynamic and multifaceted process, deeply rooted in societal values, educational philosophy, and evolving technological contexts. This study underscores the critical importance of maintaining a human-centred approach in curriculum design, even if AI becomes increasingly integrated into educational systems. While AI offers promising tools for personalization, efficiency, and innovation, it must remain a complement–not a replacement–for human educators, whose emotional intelligence, ethical reasoning, and pedagogical judgment are irreplaceable.

The research findings affirm that effective curriculum design requires a careful balance between tradition and innovation, global trends and local relevance, as well as automation and human agency. The proposed generative mechanism emphasizes a structured, iterative, and inclusive process that responds to learners' needs, industry demands, and societal change.

Ultimately, education must remain a human endeavour, empowered—but not dictated–by technology. As we move forward, meaningful collaboration between educators, technologists, and policymakers will be essential to ensure that curricula continue to inspire, empower, and prepare learners for our uncertain and rapidly changing world.

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As integration of AI into curriculum development continues to evolve, there are several key areas for future exploration and implementation. Considering the positive feedback regarding AI's potential to personalize learning, one key next step would be to develop and refine AI-supported curriculum models that allow educators to integrate technology seamlessly into their teaching practices.

In the future, the establishment of clear ethical guidelines for the development and deployment of AI in educational contexts will be crucial.

Given the increasing role of AI in education, it is essential that educators receive ongoing professional guidance and training, considering AI tools and their pedagogical applications. This will equip teachers with the necessary skills to use AI effectively, understanding both its potential and limitations. Additionally, fostering a critical understanding of AI's impact on pedagogy and learning will empower educators to make informed decisions about when and how to use AI in their classrooms.

One promising direction is the exploration of hybrid models of education that combine both human and AI-driven instruction. Such curriculum models could ensure that AI can handle repetitive tasks and data analysis, while educators continue to provide the human interaction, critical thinking opportunities, and emotional support that students need.

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LANDOLT TABLES IN PRIMO LEVI'S "BEST IS WATER" FOR VALUE-BASED CHEMICAL EDUCATION

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Abstract

As science education faces the urgent task of rehumanization amid growing technocratic rationality, scientific eponyms, especially in literary contexts, offer a potential of rehumanization for value-based science education. To explore this potential, selected passages referencing the eponym "Landolt tables" from the short story "Best Is Water" by Italian chemist and writer Primo Levi were analyzed in both the original Italian and its English translation. The focus was on anthropomorphization of the eponym, using a range of interpretative theories: existentialism, phenomenology, postmodernism, psychoanalysis, semiotics, structuralism, symbolism, and theological philosophy. The findings suggest that theological philosophy reveals the anthropomorphization of the "Landolt tables" most strongly, while structuralism does so the least. The Italian original highlights psychological and existential moments, whereas the English translation places more emphasis on logical structure and narrative progression, thereby reducing the emotional charge. These results affirm that anthropomorphized scientific eponyms can help restore science education's connection to human values, history, and morality. In doing so, they offer educators a powerful toolkit for rehumanizing chemistry instruction, nurturing not only informed minds but also empathetic and ethically attuned citizens.
Keywords: *anthropomorphization, chemical education, eponym, humanization in education, Primo Levi*

Introduction

In today's world, society faces an urgent need to counteract the ongoing process of dehumanization, particularly in the domains of science and education. Modern civilization is increasingly governed by technocratic and mechanical rationality, which tends to marginalize human values, emotions, and ethical consciousness. This condition demands a shift–a transformation from *dehumanization* to *rehumanization*. Such transformation is only possible through a comprehensive change in educational philosophy and practice, beginning with science education (Aberšek et al., 2023). The field has been identified as a particularly problematic area within modern schooling due to its detachment from humanistic and moral dimensions (Slabin, 2007).

According to Lamanauskas (2009), the current model of science education often disregards the human dimension of scientific inquiry, focusing instead on fragmented knowledge and standardized testing. Education must return to its value-based version–one that instills not only scientific literacy but also moral responsibility, empathy, and global citizenship. This value-oriented approach realigns science teaching with the broader humanistic goals of education. National educational documents across countries

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such as Belarus, Kazakhstan, Latvia, Poland, Ukraine, and the United States reinforce this notion: science education is not just the transmission of knowledge but also the transfer of cultural and ethical values (Slabin, 2017a). This broader view anchors scientific learning in the human experience.

Contributing to this discourse, Elkanova and Chedzhemova (2013) offer a nuanced examination of how humanization and humanitarization have developed within the field of education science. While *humanization* emphasizes the dignity, individuality, and freedom of learners, *humanitarization* stresses the inclusion of culture, ethics, and empathy in curricula. 40 years before this dichotomy was established, educational researchers had considered only *humanization* that "seems to have two connotations. One is the inclusion of "humanities" in science education... Including humanities is an attempt to make science instruction more relevant for today's youth, because the concepts taught in all areas of science reflect upon society... Whereas the first meaning is built around the word "humanities," the second is built around "humanitarian," that is, being involved with the welfare of the individual (Goar, 1972, pp. 23–24). Anyway, this dual framework aligns naturally with the call for a more value-oriented approach to science education.

A powerful, yet often underexplored, tool for realizing this vision lies in the use of *eponyms* in science education. Eponyms are terms derived from the names of scientists, inventors, designers, historical figures. They serve not only as didactic means (vectors of memory and meaning) and linguistic metaphors (Slabin, 2022) but also as axiological means, translating values to students (Slabin, 2019b). E.g., teaching concepts such as Avogadro's number, Le Châtelier–Braun principle, or Beschamp's reaction as more than mere terms–but as windows into the lives and struggles of those who shaped science–can powerfully humanize scientific discourse. Eponyms thus foster empathy and curiosity, linking abstract knowledge with concrete personal stories.

The humanizing potential of eponyms becomes even more significant when they appear in literary contexts. Literature creates a narrative space where the lives behind scientific discoveries can be dramatized, interpreted, and emotionally experienced. In this light, the connection between science and literature emerges not as a marginal curiosity but as a core educational strategy for humanization. As Leonardo Júnior and Massi emphasize in their analysis (2025, p. 2), literary narratives that intertwine with scientific themes help restore the affective, imaginative, and ethical dimensions of science, which are often absent from traditional curricula. Science fiction, in particular, plays a pivotal role in forging this connection. It allows for creative exploration of scientific principles while simultaneously foregrounding existential and ethical questions. It is within these narrative experiments that students encounter science as a profoundly human endeavor, replete with doubts, aspirations, and moral implications.

Italian chemist, writer, and Holocaust survivor Primo Levi stands as a paragon of this approach. His collection *The Periodic Table* blends autobiography, science, and fiction into a form of writing that rehumanizes both chemistry and the figure of the chemist. Levi portrays the chemist not as a mere technician but as a thinker, a survivor, and a narrator of truth. His work was deservedly hailed in 2006 as "the best science book ever written" (Cerruti, 2019), a testament not only to its literary brilliance but also to its philosophical depth and educational value. Levi's texts were experimentally incorporated into chemistry lessons to foster humanistic reflection alongside scientific understanding

(Osorio et al., 2007). When students read about Levi's experiences distilling benzene in presence of potassium (as a replacement for sodium) at university or passing a chemistry exam in the concentration camp, they are exposed to both the material and moral dimensions of science. This dual exposure promotes a kind of scientific literacy that is not only cognitive but also ethical.

While the term "humanization" describes many of these outcomes, it does not fully encompass all the cognitive and emotional processes at play in education. A particularly potent strategy used in both informal and formal educational settings is *anthropomorphization*—the attribution of human characteristics to non-human entities (reactions, substances, glassware, theories, postulates, equations, numbers, tables, formulas, laws, asf.). This literary and cognitive device often arises spontaneously in classroom metaphors: students may describe reactions as "angry," formulas as "mysterious," or tables as "deciding" outcomes. While such expressions may seem fanciful, they reflect a fundamental cognitive strategy that can serve a powerful pedagogical function. Far from being a fanciful distraction, anthropomorphization helps learners grasp abstract scientific ideas by embedding them in familiar emotional and social frameworks. As such, it deserves recognition as a legitimate and powerful tool for humanization in education. Analyzing the relationship between science and art in Levi's *The Periodic Table*, Massi et al. (2022) employ categories of anthropomorphization and *desanthropomorphization*.

Almost all eponyms (not only chemical) occur in Levi's *The Periodic System*. This book, along with Levi's other works, is explored by philosophers, psychologists, and philologists. Analyzing Levi's short story *Best Is Water*, Leonardo Júnior and Massi (2025) found that Levi "humanizes science and philosophical topics; problematizes the technical job of a chemist and the use of prototypes; expresses a conception of reality that is stratified and in movement, confronting neopositivist science and empirical realism; shows the importance of the chemist's sensibility in raw reality."

Research Problem

Although eponyms, especially when embedded in literary context, hold a significant potential for advancing value-based science education, their educational function remains largely underexplored. While Levi's *The Periodic System* has occasionally been examined from pedagogical perspectives (Osorio et al., 2007), existing research has not yet systematically addressed the role of eponyms, nor their capacity to foster ethical reflection, historical awareness, and humanization in science teaching.

Research Aim and Research Questions

The aim of this study was to analyze selected passages from *Best Is Water* that mention the eponym *Landolt tables*, using a range of interpretative theories, with emphasis on how these passages enact processes of humanization, anthropomorphization, and the pedagogical benefits they offer for value-based chemical education:

1. Which interpretive theory most effectively reveals the anthropomorphization of the eponym *Landolt tables* in the selected passages?
2. To what extent does anthropomorphization differ between the Italian original

https://doi.org/10.33225/BalticSTE/2025.197

and the English translation of *Best Is Water*?

3. How can the anthropomorphization of scientific eponyms, as exemplified in Levi's story, be harnessed to support humanization for value-based chemical education?
4. How does the presence of *Landolt tables* as an eponym contribute to students' historical and cultural understanding of chemistry?

Research Methodology

General Background

Analysis of literary texts traditionally involves close reading, intertextual analysis, and attention to rhetorical, symbolic, and thematic structures. Literary research often extends beyond the surface of narrative to explore deeper patterns of meaning, ideological undercurrents, and stylistic strategies. These approaches are particularly valuable when examining texts that cross disciplinary boundaries, such as Levi's creative writing.

An important method used in this study was content analysis, which allows for systematic identification and interpretation of recurring themes, symbols, and references. Content analysis is used to study specific aspects and topics in a number of chemistry textbooks (Marfuatun et al., 2024). It is especially useful for tracking the presence and function of eponyms, and the author used it in the past, studying Mendeleevian eponyms (Slabin, 2023).

To deepen this inquiry, the study utilized a set of interpretive theories selected for their shared focus on language as an analytical object. These included structuralism, semiotics, psychoanalysis, symbolism, existentialism, phenomenology, postmodernism, and theological philosophy. Although some of the listed theories are philosophical, the adjective "interpretive" is preferred over "hermeneutic" as more universal. Neopositivism was not selected because, as Leonardo Júnior and Massi (2025) observe, Levi's *Best Is Water* appears to confront and critique the assumptions of neopositivist science and empirical realism. Therefore, interpretive theories, focusing on language as an analytical object, are better suited to uncovering how the eponym *Landolt tables* is anthropomorphized and how this contributes to the humanization of science.

Sample

This research did not involve human subjects; rather, it consisted of a theoretical analysis of a selected literary text by Levi. Given that Levi's complete body of creative writing spans three volumes–amounting to 2910 pages–analyzing it in full would be an enormous undertaking. For this study, a focused and manageable sample was chosen: the six-page short story *Best Is Water*, from *The Complete Works of Primo Levi* (2015). The story's title echoes the first line of a poem by the ancient Greek poet Pindar, underscoring Primo Levi's classical education and evoking the enduring dialogue between classical and scientific cultures (Cravero, 2018): "Best is water, while gold, like fire blazing in the night, shines preeminent amid lordly wealth" (Pindar, 1997, p. 47). By the way, this Greek poet introduces another remarkable eponym–the *Pindaric style*. He employed the triadic structure attributed to Stesichorus, comprising a strophe followed by a metrically

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corresponding antistrophe and concluding with an epode, written in a contrasting metre that provided resolution.

The protagonist in this story is Boero, a young scientist, who finally earns his place in the laboratory, but finds the work–repeating viscosity measurements of water–tedious and soul-crushing. Doubt creeps in when his results don't match the values in *Landolt tables*, i.e., experimental viscosity data tables for gases and pure liquids from the German book *Physikalisch-chemische Tabellen* by Hans Landolt and Richard Börnstein, published in 1936. For this doubt, Boero's supervisor Curti berates him. Boero flees to the river Sangone, pondering whether to quit or falsify data, when he notices the river water behaving strangely. Driven by instinct, he samples it and confirms: its viscosity is 30% too high. As more rivers follow, Boero and Curti reconcile and co-author urgent reports. The phenomenon spreads–Po River thickens, then rains grow viscous across Europe, disrupting agriculture, transit, and industry. Nature shifts: trees die, cities clog, machines fail, and the world slows. Human bodies are afflicted: blood thickens, energy fades, tears cannot form, and life expectancy plummets. Europe succumbs to a new element of suffering–silent, heavy, and incurable. And from this sluggish fate, there seems to be no redemption–only a dense, creeping decline.

This particular story was selected for two key reasons that align closely with the research aim: (a) it includes a scientifically significant eponym–Landolt tables, and (b) it vividly portrays the protagonist's attitudes and emotional engagement with scientific knowledge, making it an ideal case for exploring humanization and anthropomorphization in science education.

The selected passages are presented in Table 1.

https://doi.org/10.33225/BalticSTE/2025.197

Table 1

Passages from Primo Levi's "Best Is Water" Mentioning Landolt Tables

Italian original[a]	English translation[b]
…C'era, e non era splendido come si era aspettato; non era neppure divertente, era anzi molto triste pensare a) che non basta essere in un laboratorio per sentirsi mobilitato, un soldato sul fronte della scienza; b) che avrebbe dovuto, per almeno un anno, dedicarsi a un lavoro diligente e idiota, anzi, diligente appunto perché idiota, un lavoro fatto solo di diligenza, un lavoro già fatto da almeno dieci altri, tutti oscuri, tutti probabilmente già morti, e morti senz'altro nome che quello smarrito in mezzo ad altri trentamila, nel vertiginoso indice per autori delle ***Tabelle del Landolt.***	…He had made it, yet none of it was as marvelous as he had expected it to be; it wasn't even fun. In fact, it was rather sad to think (a) that just being in a laboratory didn't make you feel mobilized, a soldier on the scientific front; and (b) that, at least for a year, he would have to dedicate himself to a diligent and mindless job, diligent precisely because it was mindless, a job that required diligence alone, a job that had already been done by at least ten others, totally unknown, all of whom were probably dead, having died without any name greater than the one lost among thirty thousand others on the vertiginous list of authors found in ***Landolt's tables***.
…Impiegò tutto il pomeriggio a ripetere le misure, ma non fece i calcoli perché non voleva guastarsi la serata. Li fece il mattino seguente, e, sure enough, la differenza rimaneva: non solo, era perfino leggermente aumentata. Ora si deve sapere che le ***Tabelle del Landolt*** sono sacre: sono la Verità. Uno viene incaricato di rifare le misure solo per sadismo, sospettava Boero: solo per verificare la quinta e la quarta cifra significativa, ma se la terza non corrisponde, ed era il suo caso, come diavolo la mettiamo? Si deve sapere che mettere in dubbio il ***Landolt*** è molto peggio che mettere in dubbio il Vangelo: se hai torto ti copri di ridicolo e ti comprometti la carriera, e se hai ragione (che è improbabile) non ne ricavi né utilità né gloria, bensì la nomea di, appunto, contabile, pignolo e insetto; e tutt'al più la gioia trista di aver ragione dove un altro ha torto, che dura lo spazio d'un mattino.	…He spent all afternoon repeating the measurements but, not wanting to ruin his evening, didn't do the calculations. He did them the following morning and, sure enough, the difference was still there, and not only that, there was even a slight increase. Now, it should be said that ***Landolt's tables*** are sacred: they are the Truth. One is given the task of retaking the measurements out of sadism, Boero suspected. Only the fifth and fourth significant figures have to be verified, but if the third doesn't correspond, and this was his case, what the hell are you supposed to do? To doubt ***Landolt***, it should be said, is far worse than to doubt the Gospels. If you are wrong, you are smothered with ridicule and risk your career, and if you are right (which is unlikely) you don't get any more credit or glory than, in fact, the accountant, the wonk, and the insect. At the very most you got the pathetic joy of being right when another was wrong, which lasted as long as a morning.

Note. [a]Italian original from Levi, P. (2015). Tutti i racconti. Ottima è l'acqua. https://dokumen.pub/tutti-i-racconti-9788858423608.html

[b]English translation from Goldstein, A. (Ed.). (2015). The complete works of Primo Levi (Vol. 1). Liveright Publishing Corporation, pp. 742–743.

Data Analysis

After close reading, the passages were analyzed from the perspectives of the eight interpretive theories.

Research Results

The results of this analysis are presented in Table 2.

https://doi.org/10.33225/BalticSTE/2025.197

Table 2

Anthropomorhization of Landolt Tables Revealed by the Eight Selected Interpretive Theories

Theory	Brief analysis of the passages from the perspective of this theory
Existentialism	Boero invests Landolt tables with ontological authority. They are no longer just scientific tools; they become arbiters of what can be known, said, or discovered. His freedom as a being-for-itself (capable of self-definition and interpretation) is constrained by the unyielding being-in-itself of Landolt tables (their fixed, authoritative presence). Boero anthropomorphizes Landolt tables in three key ways: (a) they appear to respond—negatively—to his discovery; (b) they seem unforgiving, emblematic of an absurd, unfeeling cosmos; (c) they represent a factical limit—Boero is "thrown" into a world where Landolt has already spoken, and he must now answer. This becomes a test of existential authenticity: does he conform to authority or risk the anguish of asserting originality?
Phenomenology	Boero's orientation toward Landolt tables enacts a reduction of doubt. They are not encountered as contingent or fallible but are constituted in his lifeworld as eidetic, unchangeable, and quasi-personal ideals. This is not a rhetorical embellishment; it reveals a pre-reflective structure of experience wherein the tables appear as more-than-object. Levi, through Boero, allows Landolt tables to appear with intentional force: they are not merely data, but a center of normativity. This normativity mimics subjecthood—the tables issue not facts but judgments. Thus, phenomenologically, the anthropomorphization lies in how Landolt tables live as authoritative subjectivity.
Postmodernism	From a postmodernist perspective, anthropomorphization occurs through metafictional performance. Levi uses Boero's reverence for Landolt tables as a self-aware exaggeration. The tables are elevated from a technical compendium to a sentient judge, not as a sincere belief, but as a textual maneuver critiquing the fetishization of objectivity: (a) Boero's refusal to doubt the tables arises from a narrative fiction, not rationality; (b) The anthropomorphization is ironically theatrical—it is not meant to convince but to expose the absurdity of outdated epistemic authority. Thus, postmodernism reveals a mock-anthropomorphization, one that is not genuine but performed, highlighting the constructedness of both scientific and narrative truth.
Psychoanalysis	Boero projects onto Landolt tables the role of a punishing paternal figure—a symbolic embodiment of the Law of the Father. Their silent authority functions as symbolic castration, stripping Boero of autonomy. His anxiety in being "wrong" is not merely intellectual; it is libidinal, expressing the dread of existential invalidation. The tables do not just correct—they condemn, enacting a scenario of Oedipal punishment. Anthropomorphization here occurs through projection and repression: Landolt tables become an internalized figure of judgment that shapes Boero's identity.
Semiotics	Anthropomorphization is reduced to a function of signification. Landolt tables act as a signifier of scientific objectivity, and Boero's reactions are expressions of the cultural codes surrounding that sign. Anthropomorphization is not literal but metonymic: Boero responds not to the object itself but to its position in the code of science. Thus, while signs of anthropomorphization exist, they are always secondary effects of a broader system of meaning. The subjectivity of the tables is a discursive illusion, structured by their symbolic function.
Structuralism	Structuralism reveals the underlying system in which Landolt tables operate but is ill-equipped to account for affective projection or anthropomorphic experience. It sees Landolt tables as a node in a system of epistemic relations—a position, not a presence. Boero's emotional, psychological, or spiritual reactions are flattened into functions within a linguistic or scientific structure. As a result, structuralism minimizes anthropomorphization, treating it as non-essential to the production of meaning.

https://doi.org/10.33225/BalticSTE/2025.197

Symbolism	Levi anthropomorphizes Landolt tables by portraying them not as passive repositories of chemical constants but as active arbiters of scientific truth. They are emotionally and spiritually elevated, commanding quasi-religious obedience. This portrayal is not ironic but ritualistic. Symbolically, Landolt tables become a totem of scientific orthodoxy; to question them is to commit blasphemy. Boero's intellectual crisis is framed as a struggle against the tyranny of a silent oracle. The fear of being "betrayed" by Landolt tables evokes a sense of punishment and divine judgment. Thus, in symbolic terms, the tables are not merely anthropomorphized but deified—they possess a patriarchal presence that demands loyalty, obedience, and fear.
Theological philosophy	In Boero's experience, Landolt tables are not mere scientific references; they are treated as infallible, eternal, and unchallengeable. These are not epistemic attributes but divine qualities. Viewed through this lens, Landolt tables are fully anthropomorphized as a quasi-deity, endowed with the power to judge, condemn, and sanctify. Boero's reactions—fear, awe, devotion—are read not as scientific attitudes but as acts of reverence. Theological philosophy thus clarifies the moment when Landolt tables cross the boundary from inert object to holy subject—a rare and heightened form of anthropomorphization.

As follows from Table 2, of all the theories, theological philosophy most powerfully exposes anthropomorphization by interpreting it as the result of sacralizing projection. Semiotics and especially structuralism seem to reveal anthropomorphization to the least extent. The latter is powerful in revealing how meaning is produced within systems, but it is poorly equipped to address emotive, projective, or interpersonal dimensions of anthropomorphization.

Table 3 summarizes subtle differences accompanying Landolt tables in the original and in the translation.

Table 3

Juxtaposition of Passages with Landolt Tables in Original Italian and Their English Translation

Italian source text	**Translated English version**
un lavoro diligente e idiota, anzi, diligente appunto perché idiota	*a diligent and mindless job, diligent precisely because it was mindless*
The Italian emphasizes existential futility and the paradoxical nature of diligence devoid of intellect. The English captures the meaning but renders it more gently, downplaying the emotional strain and existential despair.	
nel vertiginoso indice per autori delle Tabelle del Landolt	*the vertiginous list of authors found in Landolt's tables*
The Italian evokes vertigo as an embodied, almost nauseating response to anonymity within massified authorship. The English preserves the image but focuses on the document's structure more than its phenomenological impact.	
le Tabelle del Landolt sono sacre: sono la Verità	*Landolt's tables are sacred: they are the Truth*
Both versions render the tables as quasi-religious symbols, but the Italian capitalizes Verità to heighten their ontological authority. The English reflects reverence but with slightly less intensity.	

https://doi.org/10.33225/BalticSTE/2025.197

rifare le misure solo per sadismo	*retaking the measurements out of sadism*
The critique of scientific bureaucracy is clear in both, but the Italian feels more visceral and direct, attributing emotional malice ("sadismo") to institutional practice. The English retains the accusation but reads more like bureaucratic absurdity than cruelty.	
come diavolo la mettiamo?	*what the hell are you supposed to do?*
Both versions preserve Boero's exasperation, but the Italian has a slightly more rhetorical, internal monologue feel. The English reads more like external complaint.	
mettere in dubbio il Landolt è molto peggio che mettere in dubbio il Vangelo	*to doubt Landolt... is far worse than to doubt the Gospels*
Both versions convey theological gravity, but the Italian's phrasing is more assertive and culturally anchored. The English comparison works but slightly tones down the blasphemous connotation.	
a nomea di, appunto, contabile, pignolo e insetto	*the accountant, the wonk, and the insect*
The Italian string of insults diminishes Boero's identity in social and ontological terms. The English equivalent preserves the metaphorical sting, though "wonk" is culturally specific and may soften the dehumanization inherent in "insetto."	

As seen from Table 2, the Italian original emphasizes emotions, drawing out the affective weight of scientific labor, while the English translation generally opts for a more measured tone. In Italian, Levi highlights psychological and existential dimensions, portraying the protagonist's experience as marked by anxiety, frustration, and a sense of insignificance. The English version, in contrast, places more emphasis on logical structure and narrative progression, reducing the emotional charge. The Italian tends to personify scientific instruments and data systems, lending them a quasi-sentient presence, whereas the English frames them more as tools or frameworks. Additionally, the Italian foregrounds metaphysical and moral overtones, aligning scientific truth with theological and philosophical stakes, while the English translation moderates these aspects, offering a more secular and procedural rendering. Ultimately, the Italian text invites deeper reflection on the human condition within science, while the English seeks clarity and coherence, sometimes at the expense of pathos and symbolic density.

Discussion

Landolt tables are, in fact, a shortened form of the less commonly used eponym Landolt–Börnstein tables. The full version is likely less popular for several reasons, among them the influence of ethnocentrism (Slabin, 2017b, 2019a). It is intriguing to consider how anthropomorphizing the tables might shift if Boero had engaged with the full eponym, Landolt–Börnstein, rather than simply Landolt. From a *phenomenological* standpoint, this label would underscore the collaborative and cumulative nature of the tables' creation, disrupting their perception as a singular, authoritative source. In an *existentialist* frame, including Börnstein would further humanize the tables by emphasizing their origin in human labor rather than presenting them as an abstract, impersonal force. Through a *postmodernist* lens, the full eponym challenges the illusion of a monolithic authority, foregrounding the constructed and contingent nature of the

https://doi.org/10.33225/BalticSTE/2025.197

tables and inviting skepticism toward claims of infallibility. Further, from the perspective of *theological philosophy*, invoking Landolt–Börnstein elevates the work's symbolic sanctity. It evokes a sacred text not authored by a lone prophet but by a prophet and his apostle.

Based on the interpretive analyses of the anthropomorphization of Landolt tables in Levi's story, we can see that the ascription of human or even divine qualities to scientific eponyms opens a crucial path toward humanization in value-based chemical education. In what follows, I will elaborate on how this literary device–anthropomorphization–can be harnessed pedagogically and ethically to reframe the teaching of chemistry in more human-centered, culturally sensitive, and morally attuned ways.

Restoring affect to scientific inquiry. In Levi's portrayal, Landolt tables are not merely data; they are emotionally charged figures–guardians, oracles, patriarchs, or deities. Through Boero's reverence, fear, and awe, scientific knowledge itself becomes a locus of existential struggle. This dramatization restores affect to the scientific process. Rather than teaching chemistry as a dry accumulation of formulas and constants, educators can foreground the deeply personal encounters scientists have with authoritative knowledge: the fear of error, the joy of discovery, the pressure to conform, and the courage to dissent. This approach aligns with recent findings on the educational value of chemical eponyms for humanization and historicism (Slabin & Krasitski, 2017).

Anthropomorphization in this context is not a mistake–it is a psychological and narrative resource. It enables students to recognize that scientific practice is deeply human, grounded in values, emotions, and ethical dilemmas. By highlighting the emotional dynamics at play in even the most technical of interactions (e.g., reconciling a new discovery with an established eponym), educators can reframe chemistry as a space of moral agency and personal growth.

Recognizing the normative power of scientific authorities. Anthropomorphizing Landolt tables also unveils the normative structures embedded in scientific knowledge. As theological philosophy and phenomenology reveal, Landolt tables are experienced not just as helpful tools, but as figures of judgment and standardization–entities that impose limits, demand conformity, and validate legitimacy. When eponyms like Landolt tables are taken as absolute, they begin to act with the force of social norms.

In value-based education, this recognition becomes pedagogically generative. It invites students to question how scientific authorities are constructed, whom they serve, and what values they carry. If a table of constants can be treated as infallible, what happens to scientific creativity, diversity of thought, or marginalized perspectives? Anthropomorphization helps dramatize this tension. It lets us ask: What kind of "person" is this scientific eponym? A tyrant? A teacher? A wise ancestor? In doing so, it opens a critical dialogue about authority, humility, and the ethics of knowledge.

Bridging technical mastery and ethical reflection. One of the challenges in STEM education is the bifurcation between technical instruction and ethical or philosophical reflection. By anthropomorphizing eponyms like Landolt tables, Levi stages a convergence: Boero's technical dilemma becomes a moral and existential one. Should he challenge authority? Can truth emerge from contradiction? Is he merely wrong, or is he a pioneer?

This convergence can be a model for chemical educators. When students learn that Levi's protagonist is not simply "checking his data," but engaging in a struggle with a

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silent, omnipotent figure–Landolt tables–they begin to see science as a human endeavor. They see that empirical rigor does not exclude moral reflection; it requires it. Students can be encouraged to narrativize their own encounters with scientific challenges, to name their anxieties and convictions, and to personify the systems they feel constrained by. Such exercises make chemistry more inclusive, introspective, and humane.

Promoting historical consciousness and discursive empathy. Eponyms, by definition, carry names–human names–often of European, male, and institutionally empowered scientists. Anthropomorphization helps make these names more than citations: it makes them presences as was shown in recent research (Slabin, 2019b). In Levi's story, "Landolt" is not merely a bibliographic entry but a quasi-character with whom Boero interacts. This dramatization invites historical inquiry: Who was Landolt? Why is his name here? It also invites discursive empathy: How might different people feel in the face of such a name?

Educators can leverage this literary anthropomorphization to humanize science historically. By exploring who gets to become an eponym–and how those names function as gatekeepers or guardians of truth–students develop a deeper understanding of how science is shaped by social forces. It opens up space for discussions on diversity, inclusion, and the legacy of colonial and patriarchal systems in the construction of scientific knowledge.

Encouraging moral imagination and scientific humility. Finally, anthropomorphization cultivates moral imagination. When Landolt tables are portrayed as fallible gods or stern patriarchs, students are implicitly asked: What if these were real people? What kind of conversation would you have? Would you obey? Disagree? Plead? This narrative frame helps young scientists recognize that authority in science must be earned, not assumed. That humility–not just precision–is a scientific virtue.

Through Levi's story, the anthropomorphized eponym becomes a mirror. It reflects not just the standards of chemistry, but the fears, hopes, and moral responsibilities of those who practice it. To humanize chemical education, we must allow these reflections to surface, to be spoken, and to be shared.

The presence of Landolt tables as an eponym in Levi's *Best Is Water* offers students a unique entry point into the historical and cultural understanding of chemistry. As a named reference, "Landolt" points not only to a compendium of experimental data but also to the individual chemist Hans Heinrich Landolt, whose work in the late 19th century contributed significantly to physical chemistry. Recognizing this eponym allows students to trace the lineage of chemical knowledge, understanding that data tables are not abstract givens, but curated repositories of cumulative human labor. These tables represent decades of scientific measurement, collaboration, correction, and trust–acts deeply embedded in both historical context and cultural values of precision, reliability, and authority.

Through Levi's literary treatment, Landolt tables become more than a technical reference; they are transformed into a symbol of scientific orthodoxy and institutional memory. Levi's narrative stages a confrontation between an individual chemist (Boero) and this impersonal monument of collective knowledge. Students are thus exposed to the affective and philosophical tension inherent in working within a tradition that both empowers and limits. By framing Landolt's tables as a quasi-sacred entity–"they are the Truth"–Levi dramatizes the reverence with which scientists often regard historical data,

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while subtly questioning the human cost of such reverence: loss of creativity, fear of error, and submission to an infallible standard.

This narrative lens helps students understand that scientific culture is not neutral. It is shaped by values–of rigor, repetition, humility, and conformity–that have been historically encoded into practices like data tabulation. The fact that Levi refers to Landolt by name foregrounds the human origins of scientific systems often perceived as purely objective. Thus, the eponym fosters a sense of continuity with past generations, allowing students to see themselves as participants in a cultural and intellectual tradition. They inherit not only the data but also the ethos and the emotional entanglements embedded in the scientific enterprise.

In this way, Landolt tables–through Levi's depiction–serve as a powerful pedagogical tool, reminding students that chemistry is not just a technical field, but a deeply human one, shaped by its historical figures, cultural rituals, and evolving ethical debates.

Conclusions and Implications

This study has demonstrated that the anthropomorphization of scientific eponyms–exemplified by Landolt tables in Primo Levi's *Best Is Water*–is not only a literary flourish but a vital pedagogical strategy in value-based science education. By interpreting scientific data through human-like metaphors, Levi invites readers to experience chemistry as a deeply personal, ethical, and emotional domain. This reframing combats the alienation often associated with decontextualized technical knowledge and supports a more holistic model of scientific literacy–one that embraces both cognitive and affective dimensions. Among the interpretive frameworks employed, theological philosophy proved most effective in uncovering the sacral, reverent attitudes that students and scientists may unconsciously project onto authoritative data sources. Furthermore, the comparison of Levi's Italian original and its English translation highlights how language choices influence the emotional resonance and ethical weight of scientific narratives. Ultimately, the findings affirm that literary strategies like anthropomorphization can restore science education's connection to human values, history, and morality. In doing so, they offer educators a powerful toolkit for rehumanizing chemistry instruction, nurturing not only informed minds but also empathetic and ethically attuned citizens.

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KEYNOTE SPEAKERS

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Dr Bussotti graduated with first-class honours in History of Science and Technology from the Faculty of Humanities (degree course in History) of the University of **Pisa** on 25th November, 1991. In July 1996, he received a Ph.D. in Historical Sciences at the University of **San Marino**, with a thesis on the foundations of mathematics, wherein he analysed four authors in particular, namely **Bolzano**, **Cantor**, **Frege**, and **Husserl**. In 2005, he was appointed with a Humboldt fellowship at the LMU, Munich.
Currently, Dr. Paolo Bussotti is Assistant Professor in History of Science and Technology, at the DIUM.

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Trabzon University, Türkiye

Prof. Dr. Muammer Çalık obtained Bachelor, Master, and PhD degrees from Karadeniz Technical University, Trabzon, Türkiye. His research interests cover a wide range of areas in science and chemistry education. He holds editorial positions, including senior editor of the *International Journal of Science and Mathematics Education*, editor of *Education and Science* and the *Journal of Turkish Science Education*, and editorial board membership for the *Canadian Journal of Science, Technology and Mathematics Education*, *Problems of Education in the 21st Century*, and the *Journal of Science Learning*.

Title: EFFECTIVENESS OF SOCIO-SCIENTIFIC ISSUES-BASED SCIENCE TEACHING IN PROMOTING SCIENTIFIC LITERACY

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Title: FOSTERING COMPUTATIONAL THINKING AND CODING SKILLS IN EARLY YEARS EDUCATION

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An active contributor to the field, Dr. Papadakis has published extensively in high-impact journals on topics such as game-based learning, mobile learning applications, and ICT in education. He serves as an editorial board member and reviewer for several international journals, including *Education and Information Technologies* (Springer) and *Computers & Education Open* (Elsevier).

Additionally, he participates in EU-funded projects aimed at innovating pedagogy through technology and has collaborated with global research networks to promote digital literacy in schools.

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An active contributor to the field, Dr. Richterek has co-authored multiple publications on physics didactics and STEM education, often collaborating with international research teams. He participates in national and EU-funded projects aimed at modernizing physics curricula and enhancing teacher training programs across Europe.
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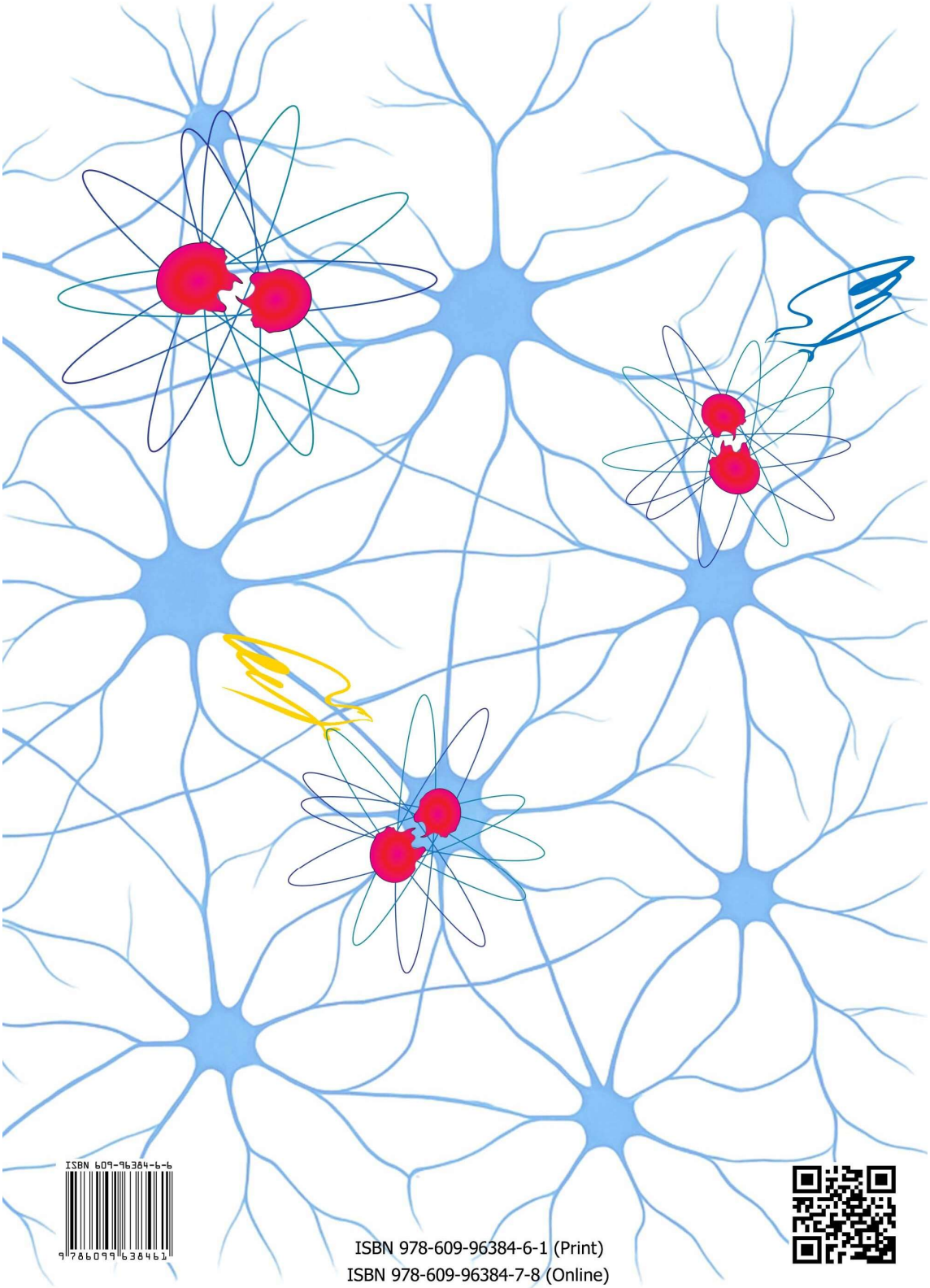

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